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COMPUTER MAPPING
as an aid in
AIR POLLUTION STUDIES

VOLUME ONE: SUMMARY REPORT

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A summary report is presented of a study of computer mapping and its application in air pollution studies. The report presents, 1. a summary of the entire project, 2. discussion of each individual study area and technical report, and 3. a discussion of some of the computer graphics produced. The report also includes, tables of contents for each of the individual reports and acknowledgements of the sources of data, and the computer programs used.

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COMPUTER MAPPING

as an aid in

AIR POLLUTION STUDIES

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PREFACE

From July 1, 1968 through December 31, 1969, the Laboratory for Computer Graphics and Spatial Analysis conducted a demonstration of several conceptual, methodological, and technical approaches to problems in the field of air pollution, employing computer-produced maps and allied displays. This work was done under a grant (No. 68A-2405D) from the Division of Control Agency Development, National Air Pollution Control Administration (NAPCA), Public Health Service, U. S. Department of Health, Education, and Welfare.

The results of this study, taken in its entirety, should make an important contribution to the work of Federal, state, and local air pollution agencies, especially in their efforts to determine the best control strategies for use in air quality control regions. The computer is an ideal tool for relating and combining sets of data, and for considering alternatives. For instance, graphic displays can contribute significantly to the evaluation of both short-term and long-term control strategies.

In demonstrating "the use of computer graphics as a means for more clearly portraying data related to the sources, distribution, and community effects of air pollution," the primary emphasis was on case studies for specific areas. The secondary emphasis, to support and complement the case studies, included:

(a) "the development of instructional manuals covering the procedures required for the preparation and interpretation of computer maps of various kinds, as related to air pollution,"

(b) "the use of certain newly developed techniques for describing, analyzing, and portraying quantitative surfaces and movements relative to such surfaces, as related to air pollution," and

(c) "an appraisal of alternative equipment, techniques, and computer programs presently or potentially available for the production of computer graphic displays pertinent to air pollution."

The case study regions were selected in consultation with NAPCA. Considerations included:

(a) sufficient air quality, emission, and related socio-economic and meteorological data--spatially distributed over the region--to enhance the likelihood of adequately demonstrating the mapping techniques;

(b) representative problems in data handling and mapping so that the techniques demonstrated would have applicability to as many other areas as possible;

(c) special problems in data handling and mapping so that as many techniques as possible could be adapted, developed, and tested;

(d) areas of which NAPCA and the individual investigators had special knowledge and could therefore utilize relevant research to enhance the study;

(e) areas where an immediate interest in mapping had been expressed for on-going Federal, state, and local air pollution activities.

Other research was undertaken to support and complement the case studies, and, in particular, to provide:

(a) the widest possible distribution of the mapping programs and accompanying explanation of the techniques through

    i) copies of the Laboratory's SYMAP Computer mapping program,
    ii) an introductory correspondence course in the SYMAP program,
    iii) general program description and supplementary explanation for the existing user-manuals;

(b) a general review of present and potential hardware, output devices, and programs applicable to computer graphic displays of air pollution and related data;

(c) means for predicting, projecting, and correlating air pollution and related data, utilizing the latest knowledge in planning, geography, and spatial analysis in general;

(d) dissemination of information on approaches and techniques to Federal, state, and local air pollution agencies, especially for use in the air quality control regions.

The final report is divided into two parts: Volume One: Summary, and Volume Two: Individual Reports--the detailed reports on the case study areas and the technical reports related to other research undertaken. The pertinent graphic displays are included with the appropriate individual report and a complete set is provided with the Summary Volume.

Introductory sections describing the air pollution and related data used are provided in the major case study reports for St. Louis and Kansas City; these should be referred to by anyone unfamiliar with the types of data and problems existing in this field. Detailed discussions of special data handling and mapping techniques are presented either as appendices to case study reports, or in separate technical reports.

The Summary Volume includes a discussion of all the areas of research undertaken and contains the complete table of contents for the reports of Volume Two. This should provide a useful reference of the special problems and technical discussions of one report which may be of interest to the reader of another detailed report.

Volume One: Summary Report, is divided into three sections: a summary of the entire project, discussion of each individual study area and technical report, and a discussion of some of the computer graphics produced. A complete set of all graphics is contained in a separately-bound appendix.

The tables of contents for each of the individual reports and acknowledgements of the sources of data, study area and technical investigators, and the computer programs used are presented before the first section. This material serves as an important introduction not only to the Summary Report but also to the individual reports of Volume Two.

John C. Goodrich, Editor
Cambridge, Massachusetts
April, 1970

VOLUME ONE
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- b. November
- c. 11-month Average

J-5 1966 Concentration of SO_2

- a. January
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- c. Average of a. and b. (Winter)

J-6 1966 Concentration of SO_2

- a. April
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J-7 1966 Concentration of SO_2

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ACKNOWLEDGEMENTS

Sources of Data

--St. Louis Region Study:

The data was provided by the Division of Control Agency Development through the efforts of Robert Stephenson, Project Officer.

The assistance of Jerry Mersch, NAPCA, the Department of Public Safety, Division of Air Pollution Control, City of St. Louis, and the Division of Air Pollution, St. Louis County Health Department, is also greatly appreciated.

--Kansas City Region Study:

Most of the data was provided by the Division of Control Agency Dvelopment, NAPCA, through the efforts of Robert Stephenson, Project Officer. The assistance of Walter Kovalick, Region V Director, NAPCA, James T. Hill, City of Kansas City, Missouri, Health Department and Richard Michael of the Kansas City - Wyandotte County, Kansas Department of Health is also greatly appreciated.

--Montreal Region Study:

The data was provided by Dr. Fabius Leblanc, S. C. Associate Professor in the Department of Biology at the University of Ottawa, and by the Service d'Urbanisme de la Ville de Montreal -- the City Planning Department of Montreal. In addition, Dr. Leblanc provided background papers and advice concerning his theories and methodology.

--Connecticut Study:

The data was provided by the Connecticut State Health Department and the Travelers Research Center of Hartford, Connecticut.

--Southern New England Study:

The data was provided by Sales Management, Inc., New York, the Commonwealth of Massachusetts, Department of Public Health, and the State of Connecticut, Department of Health. Estimates of air quality were made in conjunction with personnel of the Commonwealth of Massachusetts, Department of Public Health.

--Puget Sound Region Study:

The data was provided by J. A. Kurtzweg and D. W. Weig, through the criteria and standards development program, NAPCA.

--California Study:

The data was provided by various persons in the criteria and standards development program of NAPCA

--Boston Region Study:

The air quality data was provided by James Dallas and Cornelius O'Leary of the Air Use Management Program, Department of Public Health, Commonwealth of Massachusetts. The emissions data was provided by Gunthis Ozolins and the staff of the air quality and emissions data program, NAPCA.

Study Area and Technical Investigators

--St. Louis Region Study - Part I:

This study was under the direction of Norma Bogen, with the assistance of Donald Shepard, Steven Fosburg, Helen Mansfield, Johnny Kirkland, and Katherine Mickey. The report was principally prepared by Norma Bogen, with the assistance of Steven Fosburg, and the introductory section was adapted by Gail Howrigan.

--St. Louis Region Study - Part II;

This study was under the direction of Steven Fosburg, with the assistance of Norma Bogen and Lannon Leiman. The report was prepared by Steven Fosburg.

--St. Louis Region Study - Part III:

This study consists of a senior honors thesis for Harvard College prepared by Donald Shepard and entitled "A Load-Shifting Model to Reduce Exposure to Air Pollution Caused by Electric Power Generation."

--Kansas City Region Study:

This study was under the direction of Elia Werczberger, with the assistance of Whitmore John, Johnny Kirkland, and Steven Fosburg. The report was principally prepared by Elia Werczberger; the introductory section was adapted by Gail Howrigan.

--Montreal Region Study:

This study was under the direction of Jean-Maurice Granger, with the assistance of Steven Fosburg. The report was principally prepared by Jean-Maurice Granger, with the assistance of Steven Fosburg and Gail Howrigan.

--Connecticut Study:

The study was conducted by John C. Goodrich and Paul Jack Dangermond; the report was prepared by the investigators.

The development and administration of the SYMAP correspondence course for air pollution specialists was under the direction of Howard T. Fisher, with the assistance of John Goodrich, Donald Shepard, Laurence Yont, Donna Moorhead, and Regina McDonald.

--Southern New England Study:

The study was under the direction of William Warntz, with the assistance of John Goodrich and Steven Fosburg. The report was prepared by the investigators.

--Puget Sound Region Study:

This study was under the direction of Paul Jack Dangermond, with the assistance of John C. Goodrich and Kathleen Reine. The report was prepared by Paul Jack Dangermond and John C. Goodrich.

--California Study:

The study was under the direction of Paul Jack Dangermond. The report was prepared principally by the investigator.

--Boston Region Study:

This study was undertaken in conjunction with a masters thesis in regional planning for the Harvard Graduate School of Design prepared by John C. Goodrich and entitled "Regional Planning and Air Pollution Analysis and Control: Methodology and Case Studies." The report was prepared by the investigator.

--Computer Program Manuals:

The manuals were prepared under the direction of John Goodrich with the assistance of other members of the project and Laboratory staff, particularly Kathleen Reine, Nancy Peyton, David Sheehan, Lois Kramer, and David Sinton.

Programming support and development was under the direction of Howard T. Fisher, with the assistance of Lannon Leiman, Kathleen Reine, Donald Shepard, Change-I Hua, Ellen Bussard, Robert Cartwright, and Warnie Webster.

--SYMAP Interpolation Characteristics:

The various studies discussed in the report were carried out principally by Donald Shepard, with the assistance of Katherine Mickey. The aid of Thomas K. Peucker, Assistant Professor at Simon Fraser University, Burnaby, British Columbia, and William Warntz of the Laboratory, is gratefully acknowledged for the work discussed in section two. The report was prepared principally by Donald Shepard.

--Computer Equipment and Programs:

The report was prepared by Allan H. Schmidt, with the assistance of Adrian Thomas and John Goodrich.

Computer Programs Used in the Project

Three computer mapping programs were used in this project. The SYMAP program was used for the majority of the maps produced, particularly for maps of air quality. The GRID program--which was adapted from SYMAP to specifically handle data input in terms of a regular grid--was used in all cases where maps or data sets were compared, as in the Kansas City Region Study. Finally, the SYMVU program was used to display the three-dimensional representation of the same surface shown in two-dimensions with the SYMAP program. All three programs were developed principally at the Laboratory for Computer Graphics and Spatial Analysis. In particular, the present level of sophistication of the SYMVU program is due in large part to program development that took place during this project.

The concept, overall design, and mathematical model for the SYMAP program were developed in the autumn of 1963 by Howard T. Fisher, working at Northwestern Technological Institute. Programming was carried out by Mrs. O. G. Benson of the Northwestern University Computing Center. Since that time many others have contributed ideas and cooperated in bringing the program to its present state. Major improvements in the program were made by two Harvard students, Robert A. Russell and Donald S. Shepard, who was responsible for the algorithms on spatial interpolation. During this project significant programming developments included: more flexible user options in the map package, mating of the program with the SYMVU program, and the initial testing of Version 6.

The SYMVU program was written at the Laboratory in 1967 and 1968 by Frank J. Rens under the direction of

Howard T. Fisher. Since then it has undergone major changes and improvements, particularly during this project. The first operational version of the program was brought out as a result of this work.

The GRID program was written at the Laboratory for Computer Graphics and Spatial Analysis in 1968 by David Sinton and Carl Steinitz. The only significant development during this project was the incorporation of the SYMAP-type legends option in to the GRID program.

The user should note carefully that the Computer Program Manuals (Report K) represent the most recent versions of these three programs available from the Laboratory for Computer Graphics and Spatial Analysis and written for the IBM 360 Series Computers. The work described in many of the reports utilized earlier versions of the program--often versions written for the IBM 7094. The reader should check on which version was used before trying to duplicate or build upon the work described herein.

1. SUMMARY OF THE PROJECT

The Laboratory for Computer Graphics and Spatial Analysis has conducted a demonstration of several conceptual, methodological, and technical approaches to problems in the field of air pollution, employing computer-produced maps and allied displays. The results of this study, taken in its entirety, should make an important contribution to the work of Federal, state, and local air pollution agencies, especially in their efforts to determine the best control strategies for use in air quality control regions.

The computer is an ideal tool for relating and combining sets of data, and for considering alternatives. For instance, graphic displays can contribute significantly to the evaluation of both short-term and long-term control strategies.

The demonstration efforts concentrated, first, on various study areas and, second, on supporting technical studies. The first part of the summary report covers the significant results of both the study area and technical reports and serves as an introduction to the discussion of the reports themselves and representative graphics produced.

The demonstration grant extended over an eighteen month period and involved nearly 30 people working in some 12 project areas. Over 145 pages of computer-generated maps are presented in the Appendix to this report and in the individual study area reports of Volume Two. They represent only a small part of the possible uses of computer mapping as an aid in air pollution studies. But, they also aptly demonstrate that the mapping techniques are only as useful as (i) the data available, and (ii) the ability of the air pollution specialist and laymen alike to grasp the meaning of the information displayed.

1.1. STUDY AREAS

In demonstrating "the use of computer graphics as a means for more clearly portraying data related to the sources, distribution, and community effects of air pollution," the primary emphasis was on case studies for specific areas.

The following sections present how the study areas were chosen, what analyses were undertaken, some of the most important general findings, and examples of areas for further work. These sections are meant to serve as an introduction to the discussion of the reports in part 2, the reports themselves, and to the discussion of the graphics in part 3.

Man's activities--and especially the spatial and temporal distribution of these activities--produce dynamic patterns of air pollutant emissions. The concentrations of air pollution that result from these emissions, acted upon by the local meteorological and climatological conditions, increasingly affect man and his environment. To control air pollution, there is an immediate need for decisions concerning control policy, jurisdictional area, standards of air quality, emission control regulations, and implementation plans.

By examining available data for various study areas the attempt has been made to show how computer mapping can be a useful tool in air pollution studies, particularly for the immediate needs of control agency programs.

1.1.1. Selection of Areas

The case study regions were selected in consultation with NAPCA. Criteria included:

(a) sufficient air quality, emission, and related socio-economic and meteorological data--spatially distributed over the region--to enhance the likelihood of adequately demonstrating the mapping techniques:

(b) representative problems in data handling and mapping so that the techniques demonstrated would have applicability to as many other areas as possible;

(c) special problems in data handling and mapping so that as many techniques as possible could be adapted, developed, and tested;

(d) areas of which NAPCA and the individual investigators had special knowledge and could therefore utilize relevant research to enhance the study; and,

(e) areas where an immediate interest in mapping had been expressed for on-going Federal, state, and local air pollution activities.

The St. Louis Region was the principal study area (Reports A, B, and C.) and was selected because of the availability of data and NAPCA's interest in mapping for this region. As many of the mapping techniques as possible were tested for this region. All three mapping programs--SYMAP, SYMVU, and GRID--were used, as were data concerning measured air quality, modeled air quality, emissions, meteorology, and related socioeconomic variables. The St. Louis Region Study exemplifies the criteria of "sufficient data" and "representative problems".

The second most important study area was the Kansas City Region (Report D). It was also selected because of the availability of data and NAPCA's interest in mapping for this region. The emphasis in this study, however, was on "special problems" in data handling and mapping.

The remaining case study regions were chosen mainly because of special interest and knowledge on the part of NAPCA or the individual investigator. The Montreal Region (Report E) was chosen because of the investigator's previous study of biological indicators of atmospheric purity. The Connecticut Region (Report F) was chosen because of (1) NAPCA's interest in the modeled air quality data from the Travelers Research Center, (2) the desire to map air quality data for all of Southern New England (Report G), and (3) the possibility of using the existing Connecticut base maps for the correspondence course together with the measured air quality data. Southern New England (Report G) was chosen for the case study region for the examination of socio-economic surfaces because of (1) previous studies of potential surfaces for that area, and (2) good availability of air quality data.

The Puget Sound Region (Report H) and California (Report I) studies were selected because of specific requests from NAPCA during the project. They represent "areas where an immediate interest in mapping had been expressed". Finally, the Boston Region (Report J) was selected because of (1) the investigator's interest, and (2) the possibilities for in-depth study, due to the proximity of the data sources and agency personnel.

Some of the examples used in the technical and program reports (Reports K, L, and M) are fictitious since simplified study areas were easier to work with for the problem at hand.

1.1.2. Analyses Undertaken

A number of different analyses and mapping procedures were carried out for each of these study areas. Air quality and socio-economic data were mapped for the St. Louis Region; this included comparisons between the two, examination of diurnal variations in air quality, modeling of air quality from power plant emissions, and statistical examinations of the data.

For the Kansas City Region air quality was manipulated and mapped with particular emphasis on background values at the periphery of the study area, defining coherent areas for mapping, time-averaging of data, and comparison with air quality standards. Emission densities were mapped and air quality was compared with socio-economic data.

An Index of Atmospheric Purity was determined and mapped in the Montreal Region Study. The coverage and extent of various lichens and mosses were statistically examined and mapped to develop the best set of data for the least amount of data gathering. In addition the I.A.P. was compared to measured air quality. In the Connecticut Study air quality was mapped and compared for various time periods and comparisons were made between measured and modeled air quality. Different comparisons were made in the Southern New England Study: measured air quality, supplemented with estimated background values, were compared to socio-economic surfaces.

For the Puget Sound Region air pollutant emissions resulting from several alternative transportation plans were mapped and graphically portrayed. The transportation-related air quality mapped in the California Study reflected the influence of mountain 'barriers' to pollutant dispersion. Finally, the Boston

Region Study depicted some of the differences in surfaces based on daily, monthly, seasonal, and yearly averages.

There are a number of analyses which were undertaken that are not discussed in individual study area reports because of the incompleteness of the results. At the request of NAPCA modeled air quality for the Philadelphia Air Quality Control Region was displayed using the SYMVU program. Several examples are shown in Figures X-1 and X-2 of the Appendix. No further work was done and, therefore, no separate report was warranted.

A study was made of mapping techniques for showing point and area emissions on the same map, for the Houston Air Quality Control Region. Several approaches were tried: (i) showing area emissions as a surface, with point sources as legends on the surface, (ii) showing all emissions as a surface, (iii) showing all emissions (point and area grid cells) as separate shaded zones, and (iv) showing all emissions as zones, with point sources aggregated into area grid cells. The third technique is presently used by NAPCA with conventional graphical displays. The first technique appears to be the most accurate and graphically readable. The other two techniques are definitely misleading. No finished graphics were printed for this examination since the results were inconclusive.

A preliminary examination of the mapping of point sources--for power plants in the St. Louis area--was also inconclusive. A circle was printed using the SYMAP program around each power plant, with the size and/or the shading of the circle proportional to the pollutant emissions.* Under certain circumstances, this graphic technique can be useful, particularly when there are only a few circles and they do not overlap.

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*A similar example, using different data, can be seen in Examples 3-4 and 3-5 of Report M.

Each of the individual study area reports covers a topic of particular interest, relevant both to that study and to computer mapping as an aid in air pollution studies in general. The St. Louis reports contain (i) a general introduction to air pollution and related data, (ii) statistical analysis considerations, and (iii) diffusion modeling criteria. The Kansas City report covers questions of background values, time-averaging of data, and the use of the GRID program for surface comparisons.

The possible applications of biological indicators are discussed in the Montreal report. Modeled and measured air quality are compared in the Connecticut report while socio-economic and air quality surfaces are juxtaposed in the, Southern New England Study. Procedures for 'melding' emissions into a uniform grid are presented in the Puget Sound report, while procedures for taking into account the dispersion barrier of the mountains are discussed in the California report. Finally, the overall usefulness of computer mapping to an air pollution control agency is touched upon in the Boston report.

1.1.3. General Findings

The study area analyses of the demonstration project revealed several important general findings which are discussed in this section and, in particular, in Report M. This is by no means meant to be an exhaustive list of these findings. More detailed examinations will be found in the individual study area reports themselves.

Most air pollution data is gathered for specific geographic locations. Air quality is measured at monitoring stations or modeled for points on an x-y reference grid. Emissions data may be determined at a point--such as for a power plant--on a line--such as for motor vehicles--or over an area--such as for residential space heating. Of importance in this data gathering is the use of a common coordinate system for all air pollution data.

The usefulness of maps--and computer mapping--in air pollution studies has only recently become apparent as data have been gathered with an adequate geographic distribution over a region. Until the last few years air quality was monitored at only one or two locations in most metropolitan areas. Similarily, when emissions were estimated for an area, they were rarely allocated spatially.

Air pollution data fulfills most of the characteristics desirable for computer mapping. There is a need for accuracy, a large number of maps over time, uniformity of appearance, and--in the near future--rapid production of maps, particularly for telemetered data and emergency control systems. Computer mapping of most air pollution data is appropriate because of the large amounts of data--often in machine readable form--to be mapped and the continuing need for data display and comparison over time.

The high costs of equipment, programs, and data can be reduced by the use of shared facilities and common data transmission and storage methods. To do this an expanded national air sampling network is needed with standardized data collecting, telemetering, handling, and display. The national inventory of air quality and emissions data in Cincinnati can accomplish much of this standardization and centralization.

Most air pollution data is quantitative and assumed to be continuously variable in their geographic distribution. This includes surfaces of air quality from measured or modeled points. The handling of emissions data, however, is not so clear: area wide emissions should be represented as a continuous surface, but line or point source emissions should not.

Emission densities for area sources have generally been shown by the zones--usually grid cells--for which the data have been gathered. Point and line sources would then be shown separately or else lumped together into the zones with the area sources. This latter approach is often misleading and certainly not an advisable one to use. Cells which have major point or line sources within them appear to have much greater emission densities than adjacent cells that do not have such sources. The most meaningful display procedure would use a surface representation for area and probably line source emission densities, but would show point sources either on a separate map or as distinctive legends on the density map.

The classification of data values for mapping may take into account the general ranges of values useful to a control agency. On the other hand, particular values of interest--such as the air quality standards--may be singled out as the contour or isoline intervals. A graphic symbol or tone of gray would be assigned to each one of the levels or classes of values. When the values are assigned to classes based on an air quality standard one might have only two levels and therefore only two symbols. One level would show areas above the standard while the other area would show areas below the standard.

Contour or isoline maps provide the best representation for the majority of air pollution and related data. The conformant or zone map can be useful for qualitative data, such as opinion surveys, and for emissions data that has both been gathered by and is to be displayed by zones.

Three-dimensional representations of the contour or conformant type surfaces obviously have great applicability for purely visual display to government or civic groups. For analytical purposes they are only useful for a general understanding of the variability in the surface and for determining what classification of data values would be useful for the contour or conformant maps.

Only three computer mapping programs have been used in our air pollution studies: the SYMAP, SYMVU and GRID programs. Plotter programs such as SYMVU are useful mainly for display. The preciseness of plotter output does not make up for the delays in plotting time or the relative scarcity of pen plotters.

For the majority of air pollution mapping applications the rapid production of maps on the line printer (with commensurate lack of detail) is more appropriate than plotter output. However, whenever presentation or display is the primary consideration, plotter programs and plotter output should be seriously considered.

Printer programs such as SYMAP and GRID undoubtedly have the greatest applicability to air pollution data. The SYMAP program can be used to interpolate a surface from non-uniformally spaced data points. This flexibility is very useful for analytical purposes when one is concerned with air quality or emissions data. Once a base map has been made for an area, a data bank can be repeatedly accessed and a large series of maps run. The

SYMAP program has proven to be very useful for producing series of air quality maps over time.

The GRID program, on the other hand, displays data collected on the basis of geographic grid cells. It is, therefore, useful for comparing maps or surfaces on a cell by cell basis. One might wish to compare air quality data gathered from a sampling network with population or related data gathered by census tracts. Such a comparison can show the areas where the air quality exceeds the standard and a large number of susceptible people (such as those presently ill with respiratory diseases) live.

Two types of data manipulation programs were developed in the course of the air pollution studies. Only the first type involves data point locations. For several of the study areas it was necessary to aggregate data cells or data zones so as to have more reasonable numbers of data points for mapping. In the case of emissions data for the Connecticut Study, previously defined grid cells were simply aggregated into larger cells. In the Puget Sound Study, the emission zones were defined by the program and then the motor vehicle emissions placed in the appropriate zones.

The second type of data handling and manipulating program involved the time-averaging of data--the manipulation of the values to be mapped when the data points to be used for mapping were already known. This latter set of programs is in no way unique to computer mapping; it is necessary however, for any statistical manipulation of air quality and related data. The experiences gained with the St. Louis Region data handling problems would lead one to recommend the distribution of data banks on cards or on a common set of storage tapes or disks. It is also necessary to create a data bank compatible with the computer mapping programs. Generally, a simple program can be written to manipulate the data bank so that all variables to be mapped can be matched with their corresponding data point locations as required by the SYMAP and GRID programs.

The most significant overall finding was the usefulness of the program to display, spatially, changes over time, differences between situations such as alternative transportation plans, and comparisons with socio-economic data. This provides a valuable tool to air pollution control agencies: they can quickly, inexpensively, and visually see both historical, present, and projected or possible conditions as well as the differing levels of air quality for various control strategies.

Equally as important a finding is the need for more data, particularly for data in parts of the regions now sparsely monitored. The surfaces generated by computer mapping are only as accurate as the data used.

1.1.4. Areas for Further Work

The results of the demonstration project have shown both the usefulness of computer mapping as an aid in air pollution studies and the need for further work, particularly in providing the appropriate data, in selecting the best mapping technique for the problem at hand, and in examining air quality relative to the people affected.

The relationships between air pollution and various socio-economic data--were analyzed for St. Louis to ascertain who and what are actually being affected by air pollution. Implicit in such a study is the assumption that meaningful control procedures can be carried out only when the tolerance levels and the possible kinds of long range effects are known.

The study was limited by a lack of data in usable form. Such important variables as land use were not analyzed in detail since the data existed in graphic rather than numeric form. Since the socio-economic variables from the 1960 U.S. Census were to be compared with data collected three, four, and five years later, we had to assume that the data did not drastically change during this period. Unfortunately, we do not have sufficient data to know how "stable" air pollution surfaces are over time--relative to the surfaces of housing and population. One of the data sets used was the twenty-four hour sulfur dioxide readings, taken only during the winter months for two years. The average surface over the entire year might be quite different and lead to different conclusions. Until more comprehensive sets of data are made available, it will be difficult to draw substantive and statistically based conclusions.

A great deal can be learned about the behavior of air pollution within the area containing the sampling stations and adjacent areas. Since the concentration of observations is generally the greatest in the central city, the accuracy is usually best there. Outside the central core of observations, the extrapolated surface often becomes quite inaccurate. The extrapolated surface is an average of the nearest points; often this graphically produces areas of misleadingly high air pollution outside of the region we are examining--in areas where we would expect to find lower levels of pollution. The interpolation of the surface is better between points than outside the area containing the data points. If the points are not equally spaced, different portions of the map will be accurate to different degrees. In no case were the pollution data measured on an equally spaced grid.

If greater detail is desired, several options are available. We can (i) set up more sampling stations, or (ii) assume that air pollution behaves according to some known or hypothesized model. Available data can be fitted to such a model to estimate levels of air pollution for the region where the model is applicable. Such techniques as diffusion modeling, however, are quite complex and still too inaccurate for widespread use. Purchasing and operating more sampling stations is more immediately workable but expensive.

One solution would be to take infrequent observations around the periphery of the central city for a couple of years with mobile samplers to estimate the background level for each season, and to project the background values using straightforward statistical techniques. Background figures for each city are needed; it seems clear from what little national data we have that the background levels vary for different parts of the country. In any event we must recognize the varying accuracy of the mapped pollution surfaces, and concentrate on providing more reliable data spatially distributed over a control region.

Frequently, missing observations force us to deal with long-term averages, although in some instances they can be replaced by estimates of the data. For example, the sulfur dioxide levels for each of the sampling stations in St. Louis was averaged over all the observations at a particular station. Since the number of observations differed from station to station, the accuracy of each of these averaged values is different. Fortunately, there seemed to be no pattern to the missing data. If weekday data is substituted for missing weekend data the resulting overall average will be higher than a true weekly average. Including stations like this in an analysis of the air pollution surface can give very misleading results.

Diurnal data for SO_2 were measured at only eleven stations every two hours; consequently, the interpolated area around any missing value could be dangerously misleading. If the missing value were on what was actually a peak, the peak would not appear; if it were in a valley, the elevation of the bottom of the valley would be over-estimated by the interpolation process. Despite the anomalies caused by the missing data, it was clear that the pollution surface shifted considerably during the day. Investigations such as these will require more complete sets of data to give meaningful results.

The use of a power plant load shifting model for St. Louis (Report C) offers some promise for this approach. The load shifting offered, in one case, reductions in pollution exposure of up to 95% with less than a 5% increase in fuel and maintenance costs in the most favorable circumstances. Under conditions less favorable for load shifting, an exposure reduction of only 17% is obtained, but at an increased fuel cost of less than 2%. In most cases, the load-shifting model can attain moderate reductions in air pollution exposure, and under a few cases, it can accomplish quite remarkable reductions.

The results of the Montreal Region Study show that an urban model for air pollution evaluation with biological indicators may be designed to portray the situation in a city. One may rely mainly on a narrow strip having relatively intensive sampling along the direction of the dominant winds, with sparse sampling over the rest of the area under consideration. Some "artificial ecological settings" may also be devised using a selection of most significant species, to be used in cities where trees are barely present. Needless to say, they can hardly replace a comprehensive monitoring network in a conventional way.

The epiphytes have an intrinsic characteristic of displaying a high degree of sensitivity to the air pollution level in toto, without giving a clear indication of the most detrimental pollutant. This offers an interesting political consideration. No strong local lobbying is to be expected from businesses that pollute, since no single pollutant is identified. This I. A. P. technique could be used for American cities to preselect the most relevant cities where selective federal funds could supplement local efforts.

1.2. SUPPORTING STUDIES

The secondary emphasis of the demonstration grant was to support and complement the case studies. This included:

(i) "the development of instructional manuals covering the procedures required for the preparation and interpretation of computer maps of various kinds, as related to air pollution,"

(ii) "the use of certain newly developed techniques for describing, analyzing, and portraying quantitative surfaces and movements relative to such surfaces, as related to air pollution" and,

(iii) "an appraisal of alternative equipment, techniques, and computer programs presently or potentially available for the production of computer graphic displays pertinent to air pollution."

To accomplish the widest possible distribution of the mapping programs and accompanying techniques the following were undertaken:

a) distribution of copies of the Laboratory's SYMAP computer mapping program to 30 air pollution agencies,

b) revision of the Laboratory's SYMAP correspondence course to provide lessons specifically for air pollution specialists, and,

c) revision and expansion of the computer program manuals for the SYMAP, SYMVU, and GRID programs.

The following sections discuss the correspondence course, the use of socio-economic surfaces, the appraisal of computer equipment and programs, the computer program manuals, and various technical studies related to the computer programs.

1.2.1. SYMAP Correspondence Course

The Laboratory for Computer Graphics and Spatial Analysis distributes and administers a five lesson correspondence course designed to teach the basics of the SYMAP program to people with no prior knowledge of computer programming or the FORTRAN language. As a part of the demonstration grant efforts, the last two lessons of the course were significantly changed to reflect current data handling and information interests in the air pollution field.

The first three lessons acquaint the individual with the basic "packages" of the program, used to introduce information about

- study area outlines
- data point locations
- legends
- the values for mapping
- map size, scale, symbolism, etc.

The final two lessons show the flexibility possible in determining the output characteristics of the map, such as the value range intervals to which the data will be assigned. They also demonstrate the application of the techniques to a real world problem.

The correspondence course was written in conjunction with Version 4 of the SYMAP program; since the mapping done in this study used the newer Version 5, some of the conventions and explanations shown in the course materials do not apply and are superseded by instructions in the Computer Program Manuals. The correspondence course is not being updated to Version 5 or expanded at the present time. The use of the new Computer Program Manuals will point out the correct specifications for

Version 5 and show more advanced applications of the program. These manuals are contained in Report K.

In problem 4B of the correspondence course written for air pollution specialists, the user was asked to prepare a base map for Connecticut. One of three sets of values was then chosen for mapping. A discussion, together with the three maps and corrections to his work, is sent to the user with lesson 5. This includes, after the fact, what the user should have considered. The three maps which can result from the sets of values are 1966 air quality (upper left in Figure F-2), 1967 air quality (upper right in Figure F-2), and percent change from 1966 to 1967 (lower left in Figure F-2).

Problem 5A builds upon the results of Problem 4B and is essentially self-explanatory. With the discussion and output the user is asked to specify meaningful value range intervals for the percent change in air quality from 1966 to 1967. One of the map packages suggested to the user was used to produce the map in the lower right corner of Figure F-2. It is explained that by highlighting isolines such as the 0% change contour, we can quickly visualize areas of the study area that have importance to us.

The examples chosen and procedures employed appeared to be representative of the application of computer mapping as an aid in air pollution studies, particularly for state and local air pollution control agencies.

1.2.2. Socio-Economic Surfaces

A number of important studies have determined that good correlations can be found between socio-economic variables and spatial configurations. For example, many quantities vary according to the ratio of population divided by distance: P / r.

If for any location or point, in an area or region, the population divided by the distance to that point--for all other locations having a population--is summed, an "index of influence of population at a distance" is found for that location. Repeating this procedure so as to calculate the index of influence for all other possible locations, a surface is generated for that area; this surface is termed a "population potential surface". Further, if each population is weighted by its corresponding income, then an "income potential surface" is calculated. The income potential surface correlates well with numerous quantities and often gives better results than the population potential surface.

Repeated studies have demonstrated very remarkable correlations for the spatial patterns of social and economic phenomena with this potential of population surface for the United States. Constancy in certain phenomena is exhibited along the contours of equipotential and systematic variation in these phenomena across the potential field. For example, the following were found:

--Rural population density varies as the square of the potential;

--Rural nonfarm population density as the cube;

--Rural nonfarm rent varies as the first power;

--Land values vary as the square;

--Railroad track density varies as the first power;

--Rural free delivery route density varies as the three-halves power;

--Density of wage earners in manufacturing varies as the fifth power; and,

--Death rates vary as the square root of the potential.

The idea of potential carries with it a field quantity theory--a system of related factors (gradient, "energy", population density), each of which projects two basic "dimensions": population and distance. It may be useful to think of total influence of population in a different way:

(i) Consider that each person's influence is represented by a pile of sand, with the highest point of the pile at the place the person occupies and decreasing heights with increased distance from the person.

(ii) Suppose that there is a similarly constructed sandpile around the place of residence of every individual.

(iii) Now, let all these sandpiles be superimposed; at any point the total height of the sand will be the sum of the heights of all the individual sandpiles.

(iv) Let this height be a measure of total population influence at that point; then, a contour map or a physical model may be made of the entire surface by connecting all of the points.

Even when the idea of potential of population was first presented, it was clear that not all people could be assigned equal "weights" in the formula for influence. Not every person can be regarded as the "standard American", in terms of his ability to attract, interact, and influence at a distance. Often potential of income, rather than potential of population, is used to take into account this weight in the formula for influence.

The relationship of population and income potential to air pollution depends, primarily, on certain assumptions which have been borne out by the general similarity of the potential and pollution surfaces. Statistical analysis of the air pollution data was attempted to see if the two surfaces were as related as was evident by the first approximations.

We were limited, however, because the air quality data available for the study were unsuited for the purposes. Consequently, our results must be considered as a demonstration of techniques at this point, rather than as a statistical test of the relationship of the two kinds of surfaces.

The air quality data were inadequate for several reasons. First, each air quality sampling point represents mainly the local activity of the air pollution surface within the vicinity of the measuring station. The readings are very much influenced by local emissions of particular stationary sources, by mobile source patterns, and by the particular wind patterns. Moreover, there are too few sampling stations when we look at the study areas as a whole to sufficiently check possible errors in measurement. A high value found for a small area may not adequately represent that area in general. In short, the potentials surface is a 'smoothed' surface, but air quality often is not, when based upon measured values.

It is difficult to derive an air pollution index to correlate with potentials. The potential surface should reflect all major pollutants and, therefore, be an average air pollution indicator. We attempted to compare potential only for one year and with one pollutant, suspended particulates.

1.2.3. Computer Equipment and Programs

As a part of the demonstration grant an extensive study was made of computer equipment and programs relevant to computer mapping as an aid in air pollution studies. Many of the most pertinent findings have been discussed in a previous section.

Computer mapping of data is appropriate if some or all of the following characteristics are met:

--large amounts of data are to be mapped;

--the data are in machine readable form or can be readily converted;

--the data contain geographic codes for the zones to be mapped or include basic record identifiers which can be used to aggregate the data into zones;

--possible sources of human error in handling the data and preparing the maps are to be minimized;

--the data to be mapped measure a dynamic rather than a static phenomenon and will be updated to provide measures of change over time, or time series data are already available; and,

--accurate data are available.

Mapping projects have dealt successfully with large areas such as metropolitan regions, states and even countries, and with small areas--in one instance, with the structure of a living cell. The variables mapped have been as diverse as the study areas.

Within the next few years, the use of computer mapping is likely to increase enormously, both in quantity and in the diversity of applications. Because of the rapid growth in the use of computers, costs for a given level of capability have been dropping each year and will continue to drop. Within the next fifteen years, the equipment and knowledge required to operate and benefit from what are presently the most sophisticated systems will perhaps be within the reach of most governmental agencies. Important changes which would help to make this possible are the sharing of the same basic equipment and data by many users.

Existing applications of computer mapping fall readily into two groups: (i) military and aerospace applications, and (ii) other governmental and commercial applications. The more sophisticated applications of the military and aerospace group are related to their greater financial resources. Systems such as the military ones obviously need extensive data collection, storage and retrieval operations if they are to allow the user to communicate with the computer. Even if funds for equipment were available to governmental agencies other than the defense and aerospace group, additional funds would be needed to establish an adequate data base for use with a computer mapping system. The initial cost of constructing such a data base would in most cases be greater than the cost of the equipment required to manipulate and store the data.

Non-military applications to date have included the automatic recording and reproduction of maps for atlases and for natural resource data. Metropolitan transportation studies have often included maps of transportation networks showing such features as street capacity, actual and projected traffic volumes, origins and distinations of trips, and trips categorized by purpose or type of vehicle. Nearly all of these maps have been drawn by pen plotters.

Line printers have also been used to prepare computer maps, chiefly by organizations with a definite need for a computer mapping capability within a limited budget. The users have included urban planners, geographers, police administrators, transportation engineers, recreation analysts, and archeologists.

It is difficult to specify the computer capability required for data processing, since programs have been written for small, medium, and large computers. However, it is safe to say that size will become more critical as the state of software programs advances. Increased file manipulation and statistical analyses prior to mapping, combined with more versatile display systems, will necessitate the use of larger, more powerful equipment.

Time sharing systems, remote batch entry, and interactive graphic systems--light pen attachments for cathode ray tube scopes--all offer possibilities. Such innovations, however, will only be available on larger computers and at a few locations in the foreseeable future.

Computer mapping programs such as SYMAP and SYMVU, in their present form, require larger computers--in terms of both the size of the central processor and the complexity of the peripheral input and output equipment. Such equipment is not available to all agencies that might wish to make use of the computer mapping programs as an aid in air pollution studies.

1.2.4. Computer Program Manuals

Three computer mapping programs were used for this project: SYMAP, SYMVU, and GRID.

The SYMAP Computer Mapping Program generates two-dimensional displays showing the values of spatially distributed data, according to their actual geographic location on a base map. Combinations of standard computer printout symbols are used to print a black-to-white tone range which can correspond to a large-to small data value range. Any mathematical computations can be made on the data prior to mapping, and options are provided for the rescaling of data and for variations in symbolism.

The SYMAP program is written in Fortran IV. It can be used on a computer system equivalent to the IBM 360-40, or CDC 3600. Computer storage requirements are at least 32,000 words, or 128,000 bytes. Systems this size, or larger, are available in most government, commercial and university computation centers.

The program can produce conformant and contour maps among others. With conformant maps, predefined areas are filled with the symbol tone assigned to their data values. Contour maps show the variation of the data over the whole study area, based upon interpolation from the given data points; this type of map was used for nearly all of our demonstration efforts.

The SYMVU program provides the user with three-dimensional oblique views of a given surface by generating a magnetic tape for an incremental pen plotter. Although SYMVU was originally written in Fortran IV for the IBM 7094, it has been converted for use on an IBM 360/40 during this project.

The user of SYMVU needs to supply a matrix of surface values and a set of parameters specifying the type of oblique view desired. SYMVU is especially well suited to be run in conjunction with the SYMAP program which will generate the necessary matrix of values. The user then specifies only those options most appropriate to his needs. The program was used in this project only to produce three-dimensional views of surfaces previously mapped with SYMAP.

The GRID program is a modified version of SYMAP specifically designed for displaying data collected on the basis of a uniform geographic grid. Each grid cell may be shown on the computer-produced map as a single character or group of characters. The program displays its data using a line printer but operates more efficiently and economically because of its special purpose design which avoids the interpolation part of SYMAP. For a user who does not need the added flexibility of the SYMAP program, the GRID program can provide substanital savings.

The GRID program presently operates on an IBM 360/40. It was used for this project to produce comparison maps between two or more SYMAPs.

An extensive set of computer program manuals has been prepared as a part of the demonstration grant. These build upon the Laboratory's SYMAP Users Reference Manual, the Operators Manual, and the GRID Users Reference Manual. The result is a new seven part manual designed to cover all of the user needs for the SYMAP, SYMVU, and GRID programs.

Each of the seven parts is designed to be used separately or in combination as teaching and reference manuals. In particular, the first three sections are meant to supplement the SYMAP introductory correspondence course, and, eventually, to replace it as well as the Users Reference Manual. The fourth section is the equivalent of an intermediate correspondence course, covering the user subroutine (which gives flexibility to data input and manipulation) and the production of series of maps. The fifth section replaces the Operators Manual and covers all of the technical and programmer considerations necessary to run the SYMAP program. The five sections together represent all of the program manuals necessary to use the SYMAP program.

The sixth section covers both the user and technical considerations of the SYMVU program; it represents the first manual released for this program. The seventh section replaces the GRID Users Reference Manual; it is equivalent to the first four sections for the SYMAP program.

The user should be cautioned that the computer program manuals represent the latest version of each program. In many cases, this may not be the same version that was used for the work described in some of the individual study area reports.

1.2.5. Technical Studies

One of the significant features of the SYMAP algorithm is that it permits interpolation of a surface from points spaced unequally over a two-dimensional area. Basically, the program interpolates by taking a weighted average of the values of nearby data points. Although the form of this weighted average is fixed by the interpolation algorithm, certain parameters may be varied by the user.

The weighting of each value is based solely on the distance to the corresponding point. Intuitively, it would seem that the closer a data point, the greater should be its weighting--a property certainly satisfied by an inverse distance function. Then the question arises of which inverse distance function to choose. That is, if one data point is at twice the distance of another, how much influence should the farther point have? Since the SYMAP program was developed to handle many types of data, there seemed little theoretical reason to choose one function over another, and therefore several different weightings were tried.

Because the contouring technique in the SYMAP program is based on an interpolation function, it represents an approximation of the surface. As such, it describes trends rather than the exact value at any particular point, although the value at the location of a monitoring station itself may be considered to be "exact." The degree of exactness for other locations depends somewhat on the distance between stations. Therefore, maps should be viewed as displaying general tendencies of the data, rather than indicating precise values at all locations. Furthermore, if the nearest point to the periphery of the study area happens to be a monitoring station at which a high concentration was measured, this high value will be extrapolated to the border regardless of the distance. The result is then extrapolation of high pollutant concentrations to areas where the concentration should be approaching a lower background value.

These and other special considerations applying to the interpolation algorithm were examined during the project and are discussed in various reports, particularly Report L. This includes the use of "barriers" to inhibit or prohibit interpolation to parts of a study area. Such a procedure was particularly applicable in the case of the mountains of Los Angeles County in the California study.

Several other technical studies were undertaken during the project, as the need arose:

(i) determination of background values (Reports D and I),

(ii) calculation of missing data (Reports B and D),

(iii) development of data manipulating programs (Reports A, F, H, and J),

(iv) surface comparison and incompatible data bases (Reports B, D, and F),

(v) examination of indices of air pollution (Reports B, E, and G), and

(vi) diffusion modeling (Report C).

2. INDIVIDUAL STUDY AREA AND TECHNICAL REPORTS

The following sections briefly describe each of the study area and technical reports of Volume Two. This serves both as an abstract of each report and an introduction to the discussion of some of the graphics in the next section of the Summary Report. The discussions are by no means exhaustive of the work undertaken and described in the individual reports.

Study area reports were prepared for the following regions or states:

St. Louis -- Reports A, B, and C
Kansas City -- Report D
Montreal -- Report E
Connecticut -- Report F
Southern New England -- Report G
Puget Sound -- Report H
California -- Report I, and
Boston -- Report J.

In addition, technical reports were prepared on each of the following:

Computer Program Manuals -- Report K
SYMAP Interpolation Characteristics -- Report L, and
Computer Equipment and Programs -- Report M.

The complete table of contents for each report and acknowledgements of data sources and study investigators are covered in the beginning of this volume.

2.1. ST. LOUIS REGION

The St. Louis Region was the major case study examined under the demonstration grant. Consequently, the results are presented in three separate reports: Part I deals with the general mapping techniques; Part II with the statistical analyses undertaken; and Part III with a study of power plant load shifting.

2.1.1. Part I

The St. Louis Region Study--Part I--is presented as Report A of Volume Two. It is divided into two sections--the map system and data banks, and the maps produced in the study--in addition to an introduction discussing the area and the available data. An appendix of computer graphics produced is included.

The St. Louis study focused on levels of pollution, demographic and housing characteristics, and the relationships among these variables. The specific objectives were: (i) to map levels of air pollution; (ii) to describe the socio-economic structure of the area in spatial terms; (iii) to relate levels of pollution to demographic characteristics in order to indicate the impact of pollution on various segments of the population; and (iv) to describe the statistical relationships among the variables.

The primary technique employed was the SYMAP Computer Mapping Program. In addition, the GRID Program--which manipulates information presented in the form of a rectangular grid--was used in combination with the SYMAP program to make comparison maps of two or more sets of data. Regression analysis was used to determine the statistical relationships among the variables and to describe the surfaces of the data.

The Interstate Air Pollution Study*provided air quality, emission, and meteorological data for the period 1963 to 1965. This data was available in the printed reports of the study and in computer readable form. The majority of the data analysis and mapping was done with the measured air quality data, particularly for the winter months of 1963-1964 and 1964-1965. This air quality data was the most extensive available for any region, providing a wide range of diurnal, daily, seasonal, and climatological variability for spatial display.

None of the emissions data was mapped directly since (i) the inventory was not complete and up-to-date and (ii) better inventories could be mapped for other regions. The emissions data were used in preliminary diffusion model calculations together with the meteorological data. Because of the inadequacies of the input data and the time-consuming nature of developing and adapting advection-diffusion models, this work was later limited to a study of power plants in the St. Louis area covered in Part III.

Air quality maps were produced of the levels of sulfur dioxide and suspended particulates. Twenty-four hour concentrations of sulfur dioxide for two winter seasons were mapped as were two-hour sulfur dioxide readings throughout the day. The level of suspended particulates for a fall season, a winter season, and for a one year period were mapped.

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*Phase II Project Report, U.S. Public Health Service, Cincinnati, 1966

A series of maps was produced to describe the socio-economic structure of the area--total population and age-group population densities; percent families with low, middle, and high incomes; percent housing units in deteriorating and dilapidated condition; percent non-white population, etc.

To determine the relationships between levels of pollution and demographic variables, comparisons and statistical correlations were made between the air quality data and the census data. A map of estimated sulfur dioxide values was produced from a regression equation based on population and housing variables. Maps were also made relating specified levels of sulfur dioxide pollution to population, age-group, and income densities. In addition, maps were made relating levels of sulfur dioxide and suspended particulates to population density.

2.1.2. Part II

The St. Louis Region Study--Part II--is presented as Report B of Volume Two. It is divided into three sections--data analysis considerations, comparison of air quality and socio-economic data, and diurnal variations in air quality. An introduction discussing the area and the available data was included in Part I. Two technical appendices are included in addition to the appendix of computer graphics:

i) discussion of air quality surfaces;
ii) discussion of socio-economic surfaces.

Data handling and interpretation problems were inherent in most of the analyses done for this project.

The manner in which these problems are solved--or, in some cases, bypassed--has a strong impact on the results produced. Frequently, either the available data are not very accurate or the necessary analysis technique is unknown or experimental. In such cases, careful attention must be paid to the interpretation of the results.

A large body of socio-economic data was available for possible comparison with air pollution data. It was first necessary to select those variables which might prove to have a strong relationship to air pollution. These variables, moreover, had to be selected in terms of the immediate objectives of this portion of the study:

i) to identify those segments of the population and environment affected by various levels of pollution; and,

ii) to identify patterns of data, and combinations of patterns, that correspond in statistical terms to a high level of pollution.

Three kinds of variables were selected from the Census data: (i) population characteristics; (ii) housing characteristics; and, (iii) land use. The population characteristics selected serve as a basis for identifying the major segments of the population affected by air pollution. Population itself--in combination with other factors--is also a variable which affects the level of pollution. Housing is a variable which is affected by pollution; conversely, various types of housing contribute to pollution. Land use is an aspect of the environment that affects and is affected by pollution. All of these variables can be analyzed in terms of their spatial patterns to test their relationships to air pollution patterns.

2.1.3. Part III

The St. Louis Region Study--Part III--is presented as Report C of Volume Two. It consists of a senior honors thesis for Harvard College prepared by Donald Shepard and entitled "A Load-Shifting Model to Reduce Exposure to Air Pollution Caused by Electric Power Generation".

The report is divided into five sections--air pollution and electric power generation, elements of the load shifting model, determination of optimum solution, operating the load-shifting model, and conclusions--in addition to the acknowledgements. Two appendices are included in addition to the appendix of computer graphics produced.

This report describes the construction and evaluation of a mathematical model to reduce exposure to air pollution from the generation of electric power. Although electricity is generally not associated with air pollution, the burning of bituminous coal and residual fuel oil in steam-electric power generating plants produces a huge volume of air pollution every hour, despite certain control measures already in use.

This report presents a novel approach to control: changing primarily the location, rather than the amount of air pollution, so as to make it less objectionable. The study assumes that for economic or technical reasons it is not possible to reduce the pollution emissions beyond a certain level and that the most immediate short term abatement can be controlling the location of atmospheric concentrations.

Generally speaking, air pollution in the United States is an urban problem. Accordingly, this study focused on air pollution in a metropolitan area. Although air pollution does not respect political borders, to a large extent it respects distance: the air pollution problems of non-adjacent metropolitan areas at least 50 miles apart may generally be considered separately. This study concentrated on the St. Louis, Missouri metropolitan area, in order to benefit from a particularly intensive research study conducted in that area by Federal, State, and local air pollution agencies.

Provided demand for electricity is not so heavy as to require all plants to operate at full capacity, there is a choice of deciding which power plants to operate and at what levels. Altering the load on power plants to reflect air pollution considerations can be termed "load shifting." In this study we were concerned with total exposure to air pollution, defined as the sum of the concentrations of one pollutant, sulfur dioxide, in various "zones", times the number of people in each zone. But we were also concerned with economics: there is a cost involved in reducing air pollution which must be matched against the probable savings and benefits from the reduction.

The load shifting model used incorporates three major types of data: (1) St. Louis population statistics; (2) air pollution emission rates for each generating unit; and (3) fuel costs for each generating unit. Three rather sophisticated sub-models are used with these data: an advection-diffusion air pollution dispersion model, the SYMAP computer mapping routine, and the MFOR-01-MIP mixed-integer programming package.

The extent to which exposure may be reduced, and the accompanying dispatching pattern and cost to the power system, depend heavily on meteorological factors--especially wind direction, wind speed, and mixing depth. If the wind direction is such that there is a substantial quantity of generating capacity downwind of populated areas, then the load shifting model will conclude that very low exposure to air pollution is obtainable, particularly when there is only moderate demand for power. Wind speed has a mixed effect on the operation of the model: high wind speeds favor the spreading of the pollution over a greater downwind distance and possibly over an area of lower population density. On the other hand, high wind speed inhibits plume rise and may cause plumes to be trapped beneath the inversion ceiling, resulting in much higher ground-level concentrations. Which of these factors will predominate in a specific case can only be determined by operating the model.

The demand for power from steam-electric generating plants also affects the possible extent and cost of exposure reduction through load shifting. In general, the lower the load, the more choice there will be in dispatching generating units and the greater the shift possible to reduce exposure from power plant emissions.

2.2. KANSAS CITY REGION

The Kansas City Region Study is presented as Report D of Volume Two. It is divided into two sections--solutions to technical problems, and air pollution in the Kansas City area--in addition to an introduction discussing the area and the available data. The following technical appendices are included in addition to the appendix of computer graphics:

i) Alternative methods for extrapolating air quality data to the periphery of the study area;

ii) The use of the GRID program for the correlation of maps produced by SYMAP;

iii) Applications of the Larsen Model; and

iv) The GRID program.

Four technical problem areas, which seem to be typical for studies of this kind, were selected for this project:

a) the partial coverage of the study area with monitoring stations or data points. This situation raises problems related to the extrapolation of air quality data to portions of the region lacking monitoring stations and to the use of imposed boundary values for these areas;

b) incompatibility in the location of data points for different sets of air quality measurements, demographic or land use data, diffusion model calculations, and the like. This is often referred to as the problem of "inconsistent data bases;"

c) methods for the analysis of the spatial, social and economic implications of air pollution and of alternative air quality standards; and,

d) air quality data incompatible with suggested air quality standards in terms of averaging time, as well as the general problem of missing observations in measurement series.

The primary emphasis was on developing and discussing the techniques rather than on an examination of air pollution data for Kansas City. The techniques should have applicability to any region exhibiting similar data handling problems.

In most air pollution studies monitoring stations are very unevenly distributed throughout the region. Because of the preoccupation of such studies with high pollutant concentrations, the monitoring stations are primarily concentrated within and near the area for which air quality is either known or expected to be substandard, and, where, concomitantly, the population density is usually the greatest. Thus, most of the monitoring stations are likely to be in and around the central city, and only a few are located in the outlying portions of the metropolitan area where lower background values of pollutant concentrations can be expected.

This approach is adequate for the evaluation of air quality conditions in the most critical areas--i.e., the center of the city and surrounding area containing the main pollutant sources. But, an evaluation of the full effect of air pollution on the present population of the metropolitan area and on the expected expansion thereof required additional information on the trend of the pollution beyond the borders of the densely populated area.

Moreover, for the graphic representation of the distribution of air quality, the concentration of monitoring stations in the center of the study area is very inadequate. Contour maps drawn by hand typically show a great deal of detail near the center of the region, while the outlying areas are either entirely neglected or only very generally indicated. The problem is even more serious with respect to computer generated maps. Such maps are based on an objective-function interpolation of air quality levels between monitoring stations. Outside the area delimited by the data points the program must extrapolate the pollutant concentration based solely on the known data points. Often this extrapolation does not resemble the surface we expect.

The underlying problem is, of course, the lack of adequate boundary value conditions. In fact, little is known about the form of the decay function for the pollutant concentration from the central city to the rural background value. Although inadequate, the only solution is, therefore, an educated guess as to the decay of pollutants on the basis of the surface interpolated from measurements, and any additional available data, such as wind directions and emission densities. Procedures for determining and locating background values were developed as a part of this study.

The need for a technique for the cell by cell evaluation and comparison of SYMAP-produced maps arises whenever several surfaces are to be analyzed, and the sets of data points for the two surfaces are not coincident. When data are obtained for several variables and from different sources (such as census data, measured concentrations for different pollutants, emission inventories, land use data, etc.) quite probably the data point locations will not coincide. In every case, where the data are based on different sets of data points, there is no way to correlate the data using the conventional SYMAP program, unless we use for one of the data point sets the interpolated values at the data points of the second set. The suggested procedure uses the GRID program to compare the surfaces on a cell-by cell basis.

One of the most difficult aspects of air pollution in addition to its spatial quality is its dynamic character. For a full evaluation of the air quality of a city, we need to know not only measurements of pollution at every point and for different heights above ground level, but also records of the changes over time--during the day, for the different seasons, as well as with respect to long term trends. This problem is particularly difficult in view of our limited knowledge of the effects of air pollution on human beings in terms of length and intensity of exposure to different concentrations.

A wide range of possibilities exist in the measurement of air pollution and the manipulation of the data thus obtained. Averaging times of measurements for the Kansas City data vary between two hours for sulfur oxide and 24 hours and a month for dustfall or sulfation rates. Empirical studies have, however, often shown a lognormal distribution of concentration. Disregarding the time sequence of the different concentrations, most current studies report air quality data in terms of percentiles of the frequency distribution - geometric means, arithmetic means, and standard deviation. This array of parameters is fairly adequate with respect to the behavior of air quality for the specific averaging time selected. It says little, however, about the shorter and longer run variations of air pollution.

A mathematical model developed by Ralph I. Larsen* was used in the context of this study in two ways: (a) for the evaluation of air quality standards which differ from the measured data in terms of averaging time; and, (b) for correcting errors resulting from missing observations.

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*A New Mathematical Model of Air Pollutant Concentration Averaging Time and Frequency, Ralph I. Larsen, APCA Paper 68-147.

2.3. MONTREAL REGION

The Montreal Region Study is presented as Report E of Volume Two. It is divided into two sections--comparing conventional and biological data, and discussion of a monitoring technique based on epiphyte sensitivity--in addition to an introduction discussing the theory and methodology and the mapping techniques. An appendix of a selected bibliography is included in addition to the appendix of computer graphics.

This study was based on a theory and methodology developed by Dr. Fabius Leblanc of the University of Ottawa and other scientists, including J. De Sloover and D.N. Rao, with whom he has written articles pertaining to the pollution-indicator qualities of epiphytes. The epiphytes considered are essentially lichens and mosses, growing on trees.

The theory posits a strong negative correlation between the concentration of air pollutants (or intensity of air pollution) and the fertility and degree of coverage of lichens and mosses found growing in the area. It has been observed that as one approaches large urbanized areas or industrial complexes, epiphytes gradually decrease in vitality, coverage, and diversity of types, to such an extent that the central zones of these areas may be termed "epiphyte deserts." Further, lichens and mosses may be ranked according to their tolerance of pollutants.

Dr. Leblanc applied the method to the Montreal region. The main purpose of this Montreal study was to define a technique for evaluating the pattern and intensity of urban air pollution on the basis of epiphyte sensitivity. An Index of Atmospheric Purity was defined from the available data on number of species and coverage; various combinations of epiphytes were then analyzed and mapped to find the selection that could best approximate the I.A.P. values with the least amount of data gathering.

In studying the I.A.P. values for the Montreal region, two separate zones were established--the urban core and the rural areas surrounding it. These were then statistically examined separately and in combination with measured air quality.

Although previous studies have correlated the I.A.P. with measured air pollution levels, no detailed statistical analysis has been performed to demonstrate the relation of I.A.P. to such particular pollutants as coefficient of haze (COH), sulfur dioxide (SO_2), and insoluble residue (RES). Determining the relationship of the I.A.P. either to individual pollutants or to certain combinations of these pollutants is of considerable interest.

Unfortunately, the number of sampling stations at which these pollutants are observed in Montreal and the portion of the study area they cover are quite small. Moreover, for the data available, the I.A.P.--an indicator which changes relatively slowly--varied little over the region for which values of COH, SO_2, and RES are observed. It was, therefore, not possible to evaluate the results of the statistical analysis in this study.

2.4. CONNECTICUT

The Connecticut Study is presented as Report F of Volume Two. It is divided into two sections--the SYMAP Correspondence Course and modeling air quality--in addition to an introduction discussing the base map preparation and air sampling network. An appendix of computer graphics produced is included.

The projects which comprise the Connecticut Study were initially undertaken because of their relevancy to other study regions and supporting efforts:

i) measured suspended particulates, for the Southern New England Study, (Report G) and the SYMAP Correspondence Course; and,

ii) modeled and measured sulfur dioxide, for the modeling of the St. Louis and Boston Region studies (Reports C and J).

Although the data for Connecticut were only examined in passing, in retrospect it appears that this was among the most comprehensive air pollution information available, particularly in terms of the number and spacing of data point locations. This should be borne in mind in examining the computer maps produced for this study, particularly in relation to other studies.

The Travelers Research Center (TRC) of Hartford, Connecticut developed a regional air pollution simulation model in 1967 and 1968 for the state of Connecticut. One of the purposes of the model was to estimate the spatial distribution of air pollution concentrations across the state of Connecticut. As an input to the model, they estimated an hourly emissions inventory for the state's five major pollutants.

In addition, TRC designed a model verification program. The simulation model was tested for accuracy against actual measurements for specified time periods; this provided feedback for improvement of the model. Since model verification was carried out for specified time periods (usually a few hours), the accuracy of the emission inventory, meteorology, and modeling procedures were very important. Most air pollution simulation models determine seasonal concentrations or the annual integrated case, and do not attempt to calculate air quality for such short time periods.

The computer graphics efforts of our study concentrated on mapping the modeled and measured sulfur dioxide air quality, comparing the two, and mapping pollutant emissions. We also mapped values for suspended particulates from the state monitoring network for 1966, 1967 and 1968. These data formed the basis for the new lessons in the SYMAP correspondence course for air pollution specialists.

2.5. SOUTHERN NEW ENGLAND

The Southern New England study is presented as Report G of Volume Two. It has a section on air pollution surfaces and socio-economic surfaces for New England, in addition to an introduction discussing macrogeography and field quantity theory, and income potential as an index of air quality. An appendix describing a program to determine the critical features of a surface is included, in addition to the appendix of computer graphics produced.

Based on the results of previous studies as discussed in the first section, it was hypothesized that 'surfaces of potential' could be used as an indicator of overall air quality for a region. Potentials are an aggregate measure of the concentrations of people and their wealth; air pollution, for the most part, is also a good indication of the concentrations of people and their activities, or 'wealth'.

Preliminary investigation of the correlation of air quality with the income potential surface suggested that, when an empirically determined factor of proportionality is used, potential values can serve as a first approximation for predicting air quality. Such an index essentially reflects area source emissions and should be supplemented with other information, such as point source emission and meteorological data.

The first correlation of air quality and potential was made for data for the northeast corridor from Boston to Washington. This was by far the most encouraging correlation found between the two kinds of surfaces in our studies. However, the data bases used here were also the only reliable ones found:

(1) County values were used in both cases; generally, air quality is derived from point and area data and is not averaged for a county.

(2) Modeled air quality was used, rather than measured; this is much more apt to give a smoothed surface, similar in nature to the potential surface. Such a smoothed surface eliminates the local measuring point errors and may give a truer representation of air quality variations on the macroscale.

(3) An area source type pollutant was used. This would be more apt to reveal a smoothed surface than a pollutant such as suspended particulates, which results in large measure from point sources.

(4) A predominant wind along the axis of population reinforces the predominant socio-economic potentials interaction on this axis. A southeast wind, for instance, would have given a poor correlation.

The principal study area chosen for the examination of air quality and potentials surfaces was southern New England; the area was chosen because it had the best combinations of available air quality and potentials data. Studies of population and income potential had already been undertaken and air quality data for suspended particulates was available from several sources.

The data was not sufficient to undertake meaningful statistical correlations. Consequently, only mapping and visual comparisons were done. Again, the results were encouraging, leading to the conclusion that significant comparisons can be made once good networks of monitoring stations, or reliable modeling techniques, exist. When this is the case the potentials surfaces can be used to quickly and inexpensively estimate future macroscale levels of air quality. To develop more reasonable surfaces of air quality for correlation with income potential and other variables, measurements will have to be taken at many sites and the procedures for estimating and testing background values will have to be refined.

It was hypothesized that at a certain level of potential--associated with some determinable level of air quality--the logical boundary of an air quality control region would exist. Such an index as potential--correlating with air pollution data and being a socio-economic variable--appears to satisfy both criteria adjudged to be important in delineating regions. These criteria are air quality considerations and socio-economic factors and trends. The latter (socio-economic trends, such as population and income growth) can easily be determined with potentials. Growth areas are inherently depicted, especially when the surface is correlated with income density or population density. Secondly, if projected populations or income are used to determine the potentials, a surface of future conditions is generated. The final consideration included in delineating regions--jurisdictional boundaries--would be used to exactly fix the outline of the air quality control region, in the neighborhood of the appropriate potentials contour.

The hypothesis was tested for the Boston region at the time when the boundaries of the air quality control region were being determined. Although insufficient data were available to draw definitive conclusions, the findings were encouraging, in terms of the usefulness of the techniques.

2.6. PUGET SOUND REGION

The Puget Sound Region Study is presented as Report H of Volume Two. It is divided into two sections--computer programs and base map, and mapping of emissions data--in addition to an introduction discussing the areas and method of emission estimating. An appendix of computer graphics produced is included.

The NAPCA study carried out for this area determined the geographical distribution of motor vehicle emissions for several future transportation and urban development plans.

This study is significant because it demonstrates one of the first steps in a relatively simple technique that planning and air pollution agencies can use in the evaluation of various transportation alternatives and their implications. It should be stressed, however, that since only the projected motor vehicle emissions were determined, the technique in its present form cannot be used for meaningful comparisons of alternative land use and transportation plans. Emissions from non-vehicular sources were not determined, nor were any projected pollutant concentrations calculated.

A consistent relationship between the average route speed of a motor vehicle and the quantity of carbon monoxide and hydrocarbons emitted has been indicated by on-the-road sampling from representative automobiles. From this relationship power functions were derived indicating the pounds of pollutants emitted by vehicles per mile of travel as a function of route speed. In order to determine total motor vehicle emissions for a zone for a particular time period, we therefore need to know street lengths, average traffic volume, and average zone speed in addition to this power function.

The Puget Sound area was used for the first application of the above method since the automobile is the predominant form of transportation and a significant source of air pollution, and because a recent comprehensive study of alternative transportation and urban development patterns for the year 1985 had been made for the region.

Our project consisted of manipulating and aggregating emissions data for the several plans and mapping the results.

2.7. CALIFORNIA

The California Study is presented as Report I of Volume Two. It is divided into three sections on Los Angeles County, San Bernardino County, and the State of California. An appendix of computer graphics produced is included.

The first part of the study used data from an eleven-year investigation of carbon monoxide concentrations in and around Los Angeles County. This is among the most comprehensive set of air pollution data available, particularly for examining changes in air quality over time.

Los Angeles County is divided into three sub-regions which are relevant to this study: inland and coastal valleys, mountains, and deserts. Because of the near unique inversion situations which occur, the pollutants are often kept from dispersing out of the valley by the mountain range. Thus, the northern desert areas remain relatively free of pollution because they had little intrusion from the urbanized south and few intrinsic sources of pollution.

The major task of this study was to adequately represent the influence of the mountain range in inhibiting the flow of pollutants from the valley to the desert. Several techniques were tried to simulate the "barrier" of the mountain range. The first technique assumed that the average height of the inversion layer could correspond to a given elevation of topography. Background values placed at 5000 feet elevation proved quite useful in approximating the expected levels of pollution.

To improve upon this generalized solution a second technique was examined. The SYMAP program can take into account obstacles which might inhibit or prohibit interpolation of values to any given point. The user specifies "barriers" which are used by the program in conjunction with the interpolation procedure, as discussed in Report L. The final procedure used for making the Los Angeles County maps was a combination of permeable and impermeable barriers and the assumed background values in the mountains.

The second portion of the California study involved the mapping of values of total annual suspended dust concentration for San Bernardino County. This demonstration of the computer mapping techniques of the SYMAP program was unique in the availability of data point locations spaced adequately over the study area. The locations of the monitoring stations were selected so that each main type of landscape form and each category of population density was represented by a station. This gave a generally even distribution of stations; in addition, stations were located at the periphery of the County to measure the pollution intruding from outside the region.

The existence of data points in the mountains and deserts is in direct contrast to the Los Angeles County data. With actual 'background values' measured on the mountains and in the desert, 'dummy' mountain data points and barriers to interpolation were not necessary.

Such a sampling network can also provide valuable insight into the relative levels of suspended dust concentration resulting from:

(1) man-made sources,

(2) natural sources, such as Death Valley in the northwest corner of the County, and

(3) intrusion from surrounding areas, such as Los Angeles County to the west.

The final part of the study was concerned with an examination of air quality in relation to state-wide air quality standards. A nine month time-series of oxidant concentration as distributed across the state of California was mapped and a single month examined on a geographical basis to see how the oxidant standard had been violated.

The mapping problems for such a large region were much the same as those encountered in several of the other air pollution studies, most notably Los Angeles County and the Kansas City region. Because of the large variation across the state, in geography and landscape type as well as in settlement patterns and their resultant pollutant emissions, it is necessary to have a large number of monitoring stations to adequately represent all of the sub-regions that exist. Unfortunately, such an adequate representation is unavailable in California as it is in most states.

The number and location of data points are not the only difficulties with the monitoring network. The significant changes in topography--particularly the mountain ranges which inhibit the normal flow of pollution--need to be taken into account. In the California case two alternative techniques were used to solve this problem. As with the Los Angeles County data, the first technique was to use false or 'background' values and the second was barriers. In retrospect, although much of the mapping for this portion of the study was done using barriers, the background values technique would probably give a truer picture of air quality in a situation with as much geographic variation as California.

The choice of barriers over background values is a decision involving the scale of the project. For the Los Angeles County study barriers were a good solution; at the State scale the complexity of the geography is such that the barriers technique produces many problems and the use of background values is probably a better solution. Some combination of the two techniques may yield the best results.

2.8. BOSTON REGION

The Boston Region Study is presented as Report J of Volume Two. It is divided into two sections--data and base maps, and mapping air quality and emissions data--in addition to an introduction discussing the research methodology, some of the technical considerations, and the applicability to control agency programs. An appendix of computer graphics produced is included.

The research discussed in the report was undertaken by John C. Goodrich as part of graduate studies in the City and Regional Planning Department and was supported by an Environmental Health Research Training Grant from the Public Health Service to the Harvard School of Public Health. The report emphasizes the computer mapping aspects of the work.

The aim of the research was to develop an internally consistent methodology for examining and predicting air pollutant emissions and air quality, using available socio-economic data and relationships. Socio-economic data can be used to develop an emission inventory, to provide an index of air quality on a regional scale, and to show the spatial distribution and extent of the population groups and activities affected by air pollution. These data can also be used for projections of future levels of emissions and air quality.

The patterns of pollution for alternative distributions of people and activities can be developed and compared as part of a control agency program. Logical divisions between control regions--and the primary areas of concern within a control agency's region--can be determined without a lengthy and costly data gathering process.

The research concentrated on the inventorying and projecting of air pollutant emissions, the analysis of monitored air quality, the modeling of air quality, and the comparison of monitored and modeled data.

The Boston region was chosen as an area for study particularly because of the availability of data. A special study which monitored the air quality was conducted in 1966; this included data for sulfur dioxide and suspended particulates. An emissions inventory was conducted in 1967 for the entire region. The mapping efforts concentrated on the measured air quality and to a lesser extent on the emissions inventory data.

2.9. COMPUTER PROGRAM MANUALS

The computer program manuals are presented as Report K of Volume Two. The report is divided into seven parts:

- introduction to the use of the SYMAP program
- the data packages of SYMAP
- the Map package electives of SYMAP
- data banks and user subroutine in SYMAP
- technical considerations in the SYMAP program
- the user requirements of the SYMVU program, and
- the user requirements of the GRID program.

The manuals represent the latest versions of each of the three programs used:

SYMAP Version 5.15
GRID Version 3
SYMVU Version 1.0.

In many cases the maps discussed for each of the individual study areas were produced with earlier versions of the programs. This is particularly true when the IBM 7094 was used to produce the maps. If one wishes to use the manuals in conjunction with a study area report to replicate or build upon work done in this project, is is necessary to ascertain exactly what versions of the program were used.

The first section is a general introduction to the use of the SYMAP program. It covers the types of maps that can be produced, the requirements for coding data, and the step by step procedures that should be followed. It also describes some of the more common pitfalls one encounters in using the program.

To produce computer maps, a deck of punched cards must be prepared as input to the computer. This deck consists of a number of "packages," each covering a specific category of information. The second section gives the instructions for preparing each of the following packages:

--The OUTLINE package is used to give the coordinate locations of the vertices of the study area outline.

--The DATA POINTS package is used to give the coordinate locations to which data values are to be assigned; these locations may be either points or centers of areas.

--The LEGENDS package is used to give the coordinate locations and content of supplementary information to be printed on the map. Legends include borders, location names and numbers, the title etc.

--The VALUES package is used to assign numerical information to the appropriate data points. The values may be related, manipulated, weighted, and aggregated in any manner desired by the user subroutine.

--The MAP package is used to specify an appropriate title below each map. It is also used to specify certain "electives" which determine the form and content of the map produced.

The MAP package is always required; use of the other packages is determined by the type of map desired. The availability of the electives is described in the third section of the manuals. Some of the more important ones are:

(i) Size: used to specify the overall dimensions of the border surrounding the study area on the computer-produced map.

(ii) Content: used to change the scale of the map to be produced or to map a portion of the study area at any scale desired.

(iii) Number of Levels: used to specify the number of levels and/or contour intervals into which the total range of the data is to be divided for mapping purposes.

(iv) Symbolism: used to specify the scale of grey tones desired for mapping.

(v) Text: used to provide supplementary information below the map.

The fourth section of the manuals describes the procedures for producing more than one map at a time and for employing the user subroutine. This subroutine can be used to manipulate data prior to mapping or to transform packages to the standard coding format and coordinate system accepted by the SYMAP program. The user subroutine provides great flexibility as to the initial form of the data and the manipulations that can be performed on these data prior to mapping.

The fifth section of the manual is designed as a technical programming and systems guide. It contains the type of information formerly found in the SYMAP Operator's Manual. This includes general, programmer, system, and printer information.

The sixth section contains the information necessary to use the SYMVU three-dimensional mapping program.

It is necessary to prepare only three computer cards as data, as opposed to the numerous packages with SYMAP. Up to 32 electives can be specified on two of these cards. This provides great flexibility in the displays that can be produced.

The seventh section contains the information necessary to use the GRID Computer Mapping program. The requirements of the GRID program are similar to those of the SYMAP program. The user will find that fewer data packages are required and that many of the electives are the same as those used in SYMAP. This section covers all of the equivalent information found in the first four sections.

2.10. SYMAP INTERPOLATION CHARACTERISTICS

The technical discussion of SYMAP interpolation characteristics is presented as Report L of Volume Two. The report is divided into four sections--the SYMAP interpolation algorithm, sensitivity and accuracy of interpolation, use of electives to affect interpolation, and use of barriers to affect interpolation. Appendices on SYMAP compared to other methods of interpolation and on a map comparison program are included.

The potential user of SYMAP will best be able to understand the relation of the SYMAP algorithm to other methods of interpolation through a general understanding of the assumptions and methods of the program. The FORTRAN IV program was developed independently of any particular field to which it might be applied and consequently produces a surface with properties intuitively desirable in the absence of detailed information.

The computation part of the program takes as given the coordinates of one or more "data points" and the values associated with them. Unless otherwise specified, the surface is smooth (continuously differentiable), passes through the given points, and represents trends or patterns which those points imply. The method of calculation is a weighted average of slopes and values of nearby data points, developed from a gravity-type model.

The amount of computation is limited by computing the value at a point based only on the "nearby" data points. Given the number of data points and the area over which they extend, an initial search radius, R, is determined, such that a circle of that radius will generally contain the average number of points on which interpolation is to be based. At any character location, P, those data points whose effective distance from P is less than R are first selected. If more than the allowed maximum number of points are found, the furthest are eliminated by contracting the search radius until only the allowed number remain. If fewer than the allowed minimum number of data points are found within the initial search radius, the search radius, R, is expanded until the specified minimum number of points is reached or other constraints are met.

The interpolation algorithm gives characteristic effects when extrapolating beyond the study area. As the distance increases, all the nearest data points have roughly the same distance and direction, resulting in approximately equal weightings. Thus, the values will tend towards a limit near the average of the closest data points.

If barriers to interpolation are included for special cases such as the California Study, the algorithm is modified. The distances used in calculating weightings are "effective distances." Impermeable barriers are assigned a large strength so that the effective distance to a data point across an impermeable barrier is so large that the point is not considered a nearby data point. Interpolation from data points across the impermeable barrier is thus eliminated. The interpolation can also be modified by certain electives in the Map Package of the program.

Investigations of the type described in the report are important for the analysis of interpolated maps and for the planning of data collection schemes. At least for surfaces and the interpolation algorithm of the type considered here, data collected over a grid yields the greatest accuracy--for a given number of points. And the "error" of an interpolated surface--or the standard deviation of its differences from a reference surface--is proportional to the distance between data points on the test surface.

If we wish to prevent or inhibit interpolation from one area to another--across some line dividing the areas--we place a "barrier" to the interpolation along the dividing line. Barriers have been shown to be useful for numerous mapping situations, including:

i) planning--in mapping demographic data, to indicate that one region is separate from another. For example, the population density in New York City may be so much higher than nearby areas that it bears little relation to the surrounding densities in the metropolitan area. Without the barrier, the very high densities would extend over a much larger area than is realistic;

ii) geology--an oil company using SYMAP inserted barriers along known faults in maps of the depth of certain rock strata. With barriers, the geological maps closely resembled maps previously drawn by hand by cartographers trained in geology; and,

iii) air pollution--to describe the air pollution surface for the Los Angeles area adequately, a barrier was used to show the effect of the San Gabriel mountains north of the city, where the air pollution levels decrease rather abruptly.

2.11. COMPUTER EQUIPMENT AND PROGRAMS

The evaluation of computer equipment and programs for graphic display is presented as Report M of Volume Two. It is divided into three sections--computing machinery (hardware), computer programs (software) and types of maps, and data for graphic display--in addition to an introduction discussing the criteria for computer mapping, principles of operation, and current and future applications.

The term "computer graphics" --as used in the report--refers primarily to the nature of the data being manipulated and displayed rather than to the computer equipment which may be used. As a part of this definition of the term computer graphics, it is assumed that the data being displayed has a spatial dimension.

It may be:

(i) one dimensional-as on a bar chart;

(ii) two dimensional-as on a map or scatter diagram; or,

(iii) three dimensional-as on an architectural object or statistical surface.

Such data--especially when a geographic distribution is involved--are particularly relevant to studies concerning air pollution since the location or spatial pattern of a given variable may be as significant as its magnitude or quality.

Although maps as such are not a new phenomenon, their preparation with the aid of a computer is a fairly recent development. At the present time any conceivable map could be prepared on a computer; however, not every map should be. In evaluating the possible use of computer mapping techniques for a given application, a user should consider the characteristics of the maps desired and data to be mapped.

Computer mapping can be a significant asset as an analytical tool during a study. This is in addition to the traditional role as a descriptive tool for displaying the end results of a study. Often maps can be useful for testing and evaluating alternative hypotheses and assumptions.

The mapping applications most likely to benefit from the use of computers have one or more of the following characteristics:

--a large number of maps is needed at one time, or maps for a given area are needed on a recurring basis over a period of time;

--flexibility as to size, content, scale and data manipulation are important;

--uniformity of map appearance for many different types of data is desired;

--the time required to prepare a number of maps is to be minimized; and,

--highly accurate maps are needed; obviously, inaccurate or incomplete data should not be used, whether maps are prepared by hand or by computer. This is particularly true of computer maps because many people place unwarranted faith in anything produced by a computer.

The preparation of a computer map requires three steps: (i) input--providing the computer with data in a form acceptable to the machine; (ii) processing--the manipulation of the data and preparation of the map within the computer's memory; and, (iii) output--the actual display of a map by the computer. Not surprisingly, the computing machinery, or hardware, involved in producing computer maps and allied displays is composed of:

a) the computer itself, including the central processor and the peripheral input/output equipment;

b) the input devices, including keypunches and digitizers; and,

c) the output devices, including printers and plotters.

Graphics can be produced in some form on any of the many available computer output devices. However, the accessibility and cost of the equipment varies a great deal, as does the appearance of the graphics. The basic types of output equipment are the line printers and the mechancial or cathode ray tube (CRT) plotters.

Line printers are an integral part of almost every computer installation, making it a convenient and economical output device for computer maps. Line printers were not originally designed to print maps or other graphic displays, although they are able to produce a wide variety of computer output.

In general, the plotters are capable of providing very precise and attractive output. They are not available at every computer installation because of their cost and relatively infrequent use. At present, CRT equipment is expensive, relatively few units are available, and only a few programs for graphic display have been developed. However, all of these deficiencies are likely to be overcome in the future.

Computer mapping programs written for line printers offer the user significant economical advantages. Although maps produced by plotter programs and equipment are usually superior, printer programs and equipment can be used to prepare numerous maps rapidly and relatively economically for analytical purposes during a study, as well as for display purposes at the end of the study.

It is possible to prepare many types of maps with the computer, but no single computer mapping program is capable of producing all of them. Therefore, the choice of the type of map desired for the graphic display often determines the program to be used. The selection of the map type to be used should be based upon many considerations including assumptions about the geographic distribution of the data and its classification for purposes of display.

The data to be mapped are a major determinant in the programs and equipment to be used. Geographic data can be separated into three major categories, in terms of the coordinates required to identify location: point, line and area. An urban area may be shown, for example, as a point on a small scale map or as a bounded area on a large scale map. By increasing the scale of the map, some objects such as land parcels may still be shown as points. Each type of data requires its own method of processing and mapping.

When working with area data for two or more subjects, one often finds that the data have been collected by different zones--such as school data by school districts and health data by health districts. The most popular solution to this problem is to place a relatively fine grid over the study area. Then each school district and each health district would appear as subdivided into common units--the grid cells. The value is then uniformly distributed throughout any given zone (school or health district), and this value is assigned to every grid cell which falls entirely or predominately within the zone. This approach has often been used with area source emission inventories.

A more refined technique may be used with quantitative data by taking advantage of the surface-generating qualities of the SYMAP program. By generating a continuous surface from the data, one eliminates the assumption that a data value should be uniformly distributed throughout a zone. The entire problem of incompatible data zones can be eliminated if data for each subject can be obtained initially for small areas. Then, the data can be aggregated into a common set of larger zones.

Much of the data used by a group such as an air pollution control agency will not have been collected by that agency. Data will be sought from as wide a variety of sources as possible. In every case, however, it must be possible to transform the coordinate locations of the data into a standard coordinate system.

The three types of data differ in their storage needs. For all types, however, it is important to consider the efficiency of:

(i) adding new data to the file, as it becomes available;

(ii) retrieving data for mapping; and,

(iii) updating data in the future.

Point, line, and area data should be stored with one "record" per location with the variables related to the location on the same record. Since the area data of greatest value to air pollution control agencies is quantitative in nature and has been collected for pre-established data zones--such as area emission grid cells--the areas should be described in terms of the boundary vertices of the zone, or by the centroids if the zone sizes and shapes are uniform.

3. DISCUSSION OF GRAPHICS

In the following sections many of the computer maps and three-dimensional views produced in the project are discussed. A complete list of all computer graphics will be found in the list of illustrations--organized by study area report--and the graphics themselves are contained in the appendix to this volume, as well as in the appropriate study area report.

These sections are designed to give the reader only a glimpse of the breadth of mapping which was carried out and which is possible. They assume some familiarity with the types of data encountered in air pollution studies and should be read with the graphics themselves at hand.

The majority of computer maps produced in this study were of measured air quality. The first section describes maps of measured suspended particulates, sulfur dioxide, carbon monoxide, and oxidants for a number of areas. There is also a discussion of the diurnal variation in sulfur dioxide for the major case study region, St. Louis.

The remaining sections describe maps of comparisons of air quality with socio-economic data, as well as maps showing emission densities, modeled air quality, and biological indicators of pollution. This set of examples includes all of the types of maps produced in the project.

3.1. MEASURED AIR QUALITY

Data for measured air quality were more available for this project than any other type of air pollution information. Consequently, most of the maps produced were of measured air quality. Four categories of measured air quality are discussed in the following sections: suspended particulates, sulfur dioxides, carbon monoxide and oxidants, and diurnal variations in sulfur dioxide concentrations.

3.1.1. Suspended Particulates

Air quality maps of measured suspended particulates were produced for several of the study regions. Among these were Boston (Report J), Connecticut (Report F), and St. Louis (Report A).

In the Boston Region Study Figures J-1 through J-4 show the monthly averages for suspended particulates for January through November and the 11-month or annual average for 1966. The data for these maps were derived from daily or 24 hour readings. When we examine these maps we find a fair amount of variation in the series, both spatially and temporally. In general, the highest concentrations are in the center of the region in the vicinity of downtown Boston; this would be expected from the general concentration of pollution-generating activity in the center of the region.

A consistent set of symbolism was used throughout this set of maps; therefore, levels are comparable from one map to another. We find that the 'lightest' month is

September and the 'darkest' is February. For the month of May there are three peaks in the center of the area, rather than one main peak as we find in most of the other months and in the 11-month average. As might be expected, the 11-month average exhibits a fair degree of concentricity, whereas some of the individual months do not display this characteristic.

Without examining the data in detail it would be quite difficult to draw any conclusions from this set of maps. They are useful for understanding general trends over time and over the portion of the region mapped.

The state of Connecticut maintains a statewide monitoring network with measurements recorded for one or more pollutants in more than 20 towns. The data for the annual averages of 24 hour hi-vol readings for suspended particulates for 1966 and 1967 at 20 locations and for the first six months of 1968 at 24 locations were available for the Connecticut Study.

Figure F-1 shows the air quality surfaces for 1966 and the first half of 1968. Although the value ranges and symbolism used in the two maps are not quite the same, it is evident upon close examination that air quality significantly deteriorated from 1966 to 1968, according to the data mapped. For instance, in 1966 no area of the state exhibited readings greater than 115 micrograms per cubic meter; for the first half of 1968, 7 of the 24 data points and about a third of the state exceeded this value (the three darkest levels of symbolism in the 1968 map). To avoid seasonal bias we would have to map the first six months of 1966 rather than the whole year. Note that, since all data points are contained within the state boundaries, the symbolism shown for Long Island Sound is only an extrapolation of the values along the southern boundary of the state. This can be misleading and values for this area should generally be ignored; they represent one estimate of the trend of the air pollution surface.

The upper left-hand illustration in Figure F-2 is a map of the same 1966 air quality surface shown in Figure F-1. The striking graphical differences between the two have to do with the (1) scale of the maps, (2) value range intervals, and (3) symbolism and use of white contour lines. On closer examination we can see that such distinguishing features as the area of highest value at Ansonia are clearly evident in both maps.

The upper right-hand illustration in Figure F-2 is the 1967 air quality surface. From the symbolism used we might conclude that the air quality had deteriorated drastically from 1966 to 1967; however, different value range intervals were used and the maps demand close examination. The highest average value found for suspended particulates has actually dropped from 110 to 91 micrograms per cubic meter. The two lower illustrations in Figure F-2 show the percent change in suspended particulates from 1966 to 1967. The lower one third of the state-particularly in the southeast-does show improved air quality, while the northeastern part of the state exhibits the most deterioration in air quality, relative to the 1966 levels.

To actually quantify the change from 1966 to 1967 to decide whether or not air quality has deteriorated, we would need to compare the values for the two years at each computer character location and sum up the positive and negative differences, rather than the percent change shown in Figure F-2. We thereby weight all areas of the state equally and would find that slightly more of the state had deteriorated than had improved; 11 of the 20 data points show a relative deterioration. We could also weight our calculations by a variable such as population density to take into account the affected people as well as affected areas.

If we compare the data used in the Boston and Connecticut studies we find roughly 20 data points in each case. For the scale of the mapping nearly equal accuracy can be assumed, tempered by the distribution of data point locations. However, we should keep in mind the relative sizes of the two study areas: the Connecticut maps do not purport to have the same level of detail as the Boston maps.

The question of sampling station or data point locations was particularly important in the St. Louis Region Study. Maps for the fall of 1963, the winter of 1963-1964, and the entire period, July 1963-June 1964, were produced. These maps include the arithmetic and geometric means, and the minimum and maximum values recorded at each station (see Figures A-8 to A-13).

The largest peak concentration of particulates for the periods mapped occurred in the area of Venice and Granite City. A somewhat smaller peak occurred at the southern tip of St. Louis City and across the river from this area in Illinois. Another smaller peak occurred in the East St. Louis area. The minimum, maximum, geometric mean, and arithmetic mean maps varied somewhat as did the maps for each season. However, in spite of these variations, all maps indicated that the largest area of peak concentration was in the Venice - Granite City area.

The suspended particulate maps in Figure A-8 should not be taken too literally since there were very few sampling stations. The major black regions of the maps are attributed to a few sampling points, but give the impression that large areas are being affected by the dark level indicated. Both maps may be very misleading; for example, in the map on the left the triangular region in the highest level is attributable to only one data point in the southeastern part of the region. The remaining dark areas are due to the interpolation routine.

No outlying values were available in this case to counteract this problem. Very few points would be needed to determine the limits of the effect of high pollution regions. As it is, however, the few existing points do pick up the major pollution sources. The highest pollution sources seem to be nearest to the river. To the east of the river there do not appear to be any major air pollution emission sources within the range of the sampling stations.

Figure A-9 involves the same data as was displayed in Figure A-8. Here the arithmetic mean and geometric mean were mapped rather than the minimum and maximum values. The nature of the surfaces does not change very much from Figure A-8 to Figure A-9; the basic contours are very much the same for all four surfaces. By comparing these four maps, it is apparent that it would be very useful to be able to automatically assign data to various data intervals so as to develop a more consistent set of levels prior to mapping. The general contour lines look the same in many of these maps but the intervals often vary. In some cases the variation is not too significant. In other cases this variation is very significant. Very careful attention must be paid to the text following each map.

3.1.2. Sulfur Dioxide

Air quality maps for sulfur dioxide were produced for a number of the study areas, including Boston and St. Louis. For the Boston Region Figures J-5 through J-8 show the monthly averages for sulfur dioxide for a number of the months monitored in 1966. In addition, the two-month seasonal averages are shown for this time period. Looking at Figure J-5 we find that the month of January exhibits a predominant wind; in the seasonal average January is overshadowed by the February pattern. The same is true with the Spring average: the concentricity of the May air quality levels is quite apparent in the Spring average. The levels found in the summer months are quite low and without much variation. For this particular year there was a great deal of variability and some very high readings for the month of November, particularly during the episode period. This is reflected in the seasonal average as well. It is interesting to note that the basic patterns for both October and November are similar.

Figure J-9 shows the daily readings for the first and the fourth days of the Thanksgiving Episode period. It is apparent that the air quality has built up to quite high levels by the fourth day; on the fifth day the levels began to subside. The final illustration in Figure J-9 shows the 11-month average for sulfur dioxide. Here we see what effect the time averaging of data can have, particularly in terms of the smoothness of the surface. This surface is composed of nearly concentric circles and is in great contrast to the daily averages shown in the same illustration.

In the daily maps shown in Figure J-9 it should be pointed out that as we approach the borders of the map we have less and less information that is reliable. This is because of the interpolation algorithm of the program. At the corners of the map the program is apt to have fewer reliable data point locations to use in interpolating the values for mapping. The more the data is averaged, as in the annual case, the less these spatial variations and inaccuracies are apparent.

The maps of the St. Louis Region indicate that the highest concentrations of SO_2 occurred in the downtown St. Louis area and extended across the river during both winter seasons. (See Figure A-5.) There was an increase in the level of SO_2 at these locations from the first winter to the second winter. The greatest absolute increases in the area during this period occurred in Illinois in the vicinity of Venice and Granite City, in a portion of East St. Louis, and in a portion of Centerville (see Figure A-6). There was very little difference in the maps of the arithmetic and geometric means.

The maps which used a greater number of monitoring stations (40 versus 19) indicated higher levels of SO_2 concentrations in the area west of St. Louis City and in the

East St. Louis - Monsanto area than had been indicated when fewer stations were used (see Figure A-7).

The two-hour averages (see Figures B-1 to B-7) showed substantial fluctuation in the location of peak concentrations throughout the day. The highest concentrations appeared to move in a somewhat diagonal pattern from northwest to southeast, and back again. However, this movement was not consistent.

Figure A-2 shows the Winter network (1963-1964) for the sulfur dioxide monitoring stations, and non sulfur dioxide stations. Most of the data points are found in the center of the region, especially for the sulfur dioxide readings. There are very few rural readings. There are also very few data points as compared to the number of census tract points for the socio-economic data. (Figure A-1) In addition data were often not available for all of these locations.

The maps in Figure A-5 exhibit very little local variation even in the center. The errors of the system which allow interpolation out to the borders of the region based on only 19 clustered points are very evident. One single point affects a large triangular region coming out from the center. For these maps only the central part of the region should be considered.

For the two years (63-64 and 64-65), different levels were used. For example, the 63-64 map has about 60% of its points in the upper level; the 64-65 map has only about 28% in the upper level. Considering that the absolute value range for the 63-64 map is about twice as large as that for the

64-65 map, this is not surprising. Figure A-6 shows the difference between the two previous maps. The maps in Figure A-7 are 24 hour readings using two different means of averaging. They are practically identical, indicating that it really does not matter whether we work with arithmetic or geometric means for this set of data.

3.1.3. Carbon Monoxide and Oxidants

The best air quality data related to automobile emissions were available for various study areas in California (Report I). Data for carbon monoxide and oxidants were mapped. Various maps were produced for Los Angeles County. The first set of maps shows the measured maxima carbon monoxide concentrations (calculated using eight-hour values) for the years 1958 thru 1962 (Figures I-5 thru I-7). Figure I-5a shows the measured maxima for the entire time period 1956 thru 1967.

If one quickly examines each of the maps of this time series a definite pattern of carbon monoxide concentrations emerges. The major centers of concentrations are in Watts and the San Fernando Valley. This pattern is further evidenced in the map for the 0.1 ppm percentile (Figure I-8b--percent of the time concentration exceeds 0.1 ppm). Figure I-8a shows the geometric mean of the maxima values for 1956 thru 1967. When this map is compared to the measured maxima (Figure I-5a) it is apparent that the areas which have the extreme maximums are also the same areas having overall higher average concentrations.

For San Bernardino County the total annual suspended dust concentration for 1966, based on the geometric mean of the samples taken at each of 20 stations, was mapped and is shown in Figures I-9 and I-10. The highest concentrations occur in three areas, each resulting from a different type of source.

The center map in Figure I-10 shows the geometric mean of samples taken at 18 stations in 1967 for total annual suspended dust concentrations. Since the value range and symbolism are the same as for 1966, the two maps are directly comparable. However, it is very significant that the two mountain area stations were not used in 1967; therefore, interpolation takes place directly from the southwest corner across the mountains to the desert valley to the north. In 1967, the highest readings were found in the desert region and not in the urbanized southwest corner of the County. These high readings could have been caused by an increase in either (1) natural background particulate matter due to a high incidence of dust storms, or (2) man-made particulate matter in certain towns.

The right-hand map in Figure I-10 shows the absolute increase or decrease in total annual suspended dust concentration from 1966 to 1967. From this map we can see that the greatest increase in air pollution was in the desert region where the high readings were found for 1967. It is not possible to determine whether this increase is due to changes in man-made sources, natural background, or both. Another very large increase occured at a steel mill but this increase did not show up as strongly because of the close proximity of other monitoring stations, with either very low increases or actual decreases. This would seem to indicate that the dispersion of the pollution from the steel mill is not significantly increasing over the area as a whole, although the emissions of particulate matter are locally increasing. This is certainly a function of the scale of the map, and the placement of the monitoring stations.

Figure I-11 shows the geometric mean of the total suspended dust concentrations for the Spring, Summer, and Fall seasons in 1966. These were mapped with the same value range intervals and symbolism as the annual maps for 1966 and 1967; therefore, the maps are directly comparable. For all three seasons data were available at the 20 monitoring stations, including the two mountain area locations.

The nine maps for the state of California in Figures I-12 thru I-14 are a time sequence for monthly averages from November of 1967 thru July of 1968. The values are the maximum hourly averages for oxidant. The same isopleths and symbolism are used for each map. Examination of the time series in Figures I-12 thru I-14 shows that the lowest levels occured in December and the highest in July, on the average.

The center map in Figure I-13 demonstrates a technique for delineating areas which exceed a standard during a given period of time. The data used were the daily maximum hourly average concentrations of oxidant measured in ppm for the month of March, 1968. The dark areas represent areas where the concentration of oxidant was greater than 0.1 ppm for three consecutive days, or seven days over a three-month period from February through April.

This technique of graphically showing areas where standards have been exceeded can be used with either a single pollutant or several pollutants in combination, as in the Kansas City Region Study. It can be very useful to a control agency, particularly when a time series of maps is produced.

3.1.4. Diurnal Variations

In studying air pollution, we are concerned not only with the average levels of pollution, but also with the actual levels at any one time, since it is the actual levels that affect people. Furthermore, we are concerned with those areas where the levels are highest--the locations of the peaks on the air pollution surface. If the major contribution to a high average level of sulfur dioxide comes from peaks in a relatively uninhabited area, we may be less concerned than if the major contribution to a lower average level of SO_2 comes from peaks in an area highly populated during the day or night.

Contour and oblique view maps were produced for a two-day period from the two-hour sequential sulfur dioxide data for St. Louis. These maps showed how the levels of air pollution change during the day and what areas are most affected. (See Figures B-1 to B-7). Preliminary investigation of the results indicated that the changes in the surface during the day were due less to winds and other such climatological factors, and more to differences in emissions. This would favor control legislation which would regulate the times at which certain emitters could operate at peak capacity.

Figures B-1 thru B-7 rather dramatically reflect the changes in air quality during the day from area to area. Some of the changes are due to missing data. The data were selected so as to minimize the missing values, but often major fluctuations appear from one 2-hour period to the next for a location because only one value was missing. There were only about eleven data points for the entire surface. Fortunately, the maps were restricted to the center of the region and thus, there was not a significant problem with edge effects and the interpolation algorithm.

Care must be exercised in comparing the contour maps; they have an equal number of data points in each level and not an equal value range. The variations in the surfaces are more clearly evident in the three-dimensional views. Such an analysis could be enhanced by a more detailed study relating the changes over the surface with the actual changes in emissions and any control measures in effect.

3.2. COMPARISON WITH SOCIO-ECONOMIC DATA

The simplest way of relating air quality data and socio-economic information such as population or housing data is by means of overlays. Assuming that the maps are at the same scale and cover the same geographic area, a visual analysis of the relationships between two sets of data can be made. Each of the maps can also be used as an overlay for other kinds of mapped data--for example, air quality data can be related to topographic maps or to air quality standards for various other pollutants.

This method is direct and immediate. Moreover, a wide range of analyses is possible if a set of maps is made by changing only the intervals used. A disadvantage of this kind of analysis is that overlays may at times be difficult to read, and detail may be lost. In addition, it does not take advantage of the computer techniques which permit combinations and manipulations of data to be made and mapped in one step.

Comparison maps typically use very few levels. For example, level one might represent that part of the region in which both sulfur dioxide concentrations and population density were higher than certain standards or thresholds. Level four might represent the areas where both variables were lower than the thresholds. Levels two and three would then describe those areas where one or the other variable exceeded the threshold.

A possible disadvantage of this method is that data must relate to specified levels. For air quality data, this presents no apparent difficulty, since the level chosen can be a specified standard. However, for other kinds of data there may be no "critical level". Since the analysis is dependent on a chosen level, the mean might in this case serve as a useful threshold. The use of a series of maps using different levels as a basis for comparison can also obviate this problem.

For the St. Louis Region Study (Reports A and B) a series of maps (Figures A-14 to A-16) was made relating levels of sulfur dioxide to each of three variables: population density, density of population aged 65 and over, and density of population under age 10. Two threshold levels of SO_2 (.03 and .04 ppm) were related to the averages for the density data to demonstrate the intersection of the two sets of information. The resulting maps proved to be quite similar in overall patterns, but differed in detail. When a threshold level of .03 ppm was used, the area affected by this or a higher level included East St. Louis, Granite City, most of the city of St. Louis, and an area extending somewhat beyond the city to the west. When a threshold level of .04 ppm was used, the area affected by this level or higher included East St. Louis and the center and southwest portions of the city of St. Louis.

Care must be taken not to attach too much value to the outlying portions of the study area. The more accurate part of the region is the center. By comparing the maps we can see what part of the region corresponds to the level between .03 and .04 ppm. It appears from the maps that the central part of the city is the one with both the highest air pollution levels and population density. This is, therefore, the most 'affected' part of the region.

Figure A-15 compares SO_2 with the density of the population under age 10. There are great similarities with the surfaces of Figure A-14. The same levels of SO_2 are being used and at the .03 ppm level a significantly larger region falls into level four. However at the .04 ppm level, Figures A-14 and A-15 are quite similar for level four.

Figure A-16 demonstrates the same effect using the density of the population over age 65. These maps would have produced a more graphically useful series if there had been a more precise air monitoring network, with more data points. In such a case, we could superimpose a grid for the city on nearly a block by block basis and point out which populated blocks are most affected by the high levels of air pollution. For example, we could produce comparison maps showing where most of the elderly are found and the air pollution exceeds a certain level. The present maps are, however, on a rather gross scale and have only four levels. The fourth level includes a large percentage of the city; it would be preferable to show more detail for such a large segment of the central city.

Comparison maps (Figure A-17) were also produced relating a specified level of SO_2 (.04ppm) and specified levels of suspended particulates (75 and 120 μ/m^3) to the mean of the population density. The area of intersection of these three sets of data included the downtown section of St. Louis and the area adjacent to it. When the level of particulates was changed from 75 to 120, there was only a slight difference between the maps, indicating that nearly all of the area described was affected by a level of 120 or higher.

It appears that the highest levels of sulfur dioxide occur--and presumably have the greatest impact--in the areas where:

i) the highest density of population occurs;

ii) the greatest density and proportion of the aged live;

iii) the greatest density of children exists;

iv) the greatest proportion of the non-white population lives; and

v) the greatest density and proportion of the poor are.

In terms of this particular pollutant, it is apparent that the character of the central and core areas differs considerably from that of the suburbs and peripheral areas. A contributing factor in this case is likely to be the tendency for the proportion and number of housing units heated with coal or oil to be higher in the older and poorer areas. In addition, the location of various industries which use substantial amounts of coal and oil may be an important factor.

The relationships between suspended particulates and socio-economic characteristics, however, are not clear. The type of pollutant may well be more closely related to land use and land use activities than to demographic variables such as population and housing.

Correlations were made between different air quality standards for the Kansas City Region Study (Report D).

The implications of the different standards for the same averaging period, such as annual geometric and arithmetic means, and the distribution of areas not meeting the standards for different pollutants are of special interest.

The intersections of the different 'substandard' areas for the three pollutants were mapped. (see Figure D-22.) 'Multiproblem areas' were identified, showing that portions of the region meet only one of the standards. Some parts of the region do not meet any of the standards.

In Figure D-23 the air quality standards for the three pollutants were compared with the non-white population. It was found that nearly all of the areas with greater than 25% non-white population were also areas where the air quality standards were exceeded.

3.3. EMISSION DENSITIES

Data on air pollutant emissions were analyzed and mapped for several study areas, including the Boston Region (Report J), the Puget Sound Region (Report H) and The Kansas City Region (Report D).

Figure J-10 in the Boston Region Study shows the average annual emission density for suspended particulates and sulfur dioxide according to the 1967 inventory conducted by NAPCA. The third illustration shows the 1965 population density, based on population by towns. If we compare the average emission densities from the inventory with the 1965 population density by towns, we find a very revealing similarity. Two statements can be made about this similarity. First it tends to substantiate the contention that the Rapid Survey Technique* of emission inventorying is crude in its reliance upon population distribution as the main indicator of emissions.

Second, and conversely, if we are in need of a crude representation of emissions on short notice for a control agency program, we can use population density as a first approximation. Of interest for planning as well as for air pollution control is the excellent manner in which Route 128 follows the contour of 2500 people per square mile, except in the slowest growth area in the region, the southwest sector. There are quantifiable emission densities which correspond to this level of population density.

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*U. S. Department of Health, Education and Welfare, Public Health Service, Division of Air Pollution Control, "Rapid Survey Technique for Estimating Community Air Pollution Emissions", Cincinnati, Ohio (October 1966).

In the Puget Sound Region Study, emissions from several alternative transportation plans were analyzed and mapped. The first transportation system which was mapped for its pollutant emissions was the "Cities and Corridors" plan. This particular scheme is a comprehensive planning approach for regional transportation and urban development. Emissions for three pollutants were mapped from this plan. Figure H-1 shows carbon monoxide, Figure H-2 carbon dioxide, and Figure H-3 hydrocarbons. On each of the maps in this series one can recognize the corridor pattern of motor vehicle emissions as well as nodes of higher emission concentration and urban centers with extremely high pollutant emission levels.

The other transportation situation mapped is a continuation of the existing trends with minimum governmental planning control. When this system was mapped it showed a typical pattern of emissions ringing out from the main urban cores of Seattle and Tacoma to the peripheral suburbs. The only pollutant mapped was carbon monoxide (CO) (Figure H-4). It was selected because of its relative importance and because it was quite similar to the other pollutant emission patterns.

The next phase of the project was to look at the differences between the two transportation alternatives. The two data sets were subtracted from each other, leaving positive and negative remainders. This data was then used to make two maps (Figure H-5 and Figure H-6) showing areas of either greater or lesser carbon monoxide levels as a result of the emissions from either one or the other transportation alternative.

When we analyze the two different maps we find immediately that System 32 emissions (Plan A: continuation of existing trends) significantly exceed System 35 emissions in the major urban areas and surrounding suburbs (Figure H-5). Moreover, when we visually examine the companion map (Figure H-6) where "Cities and Corridors" emissions exceed those associated with the continuation of existing trends, we find the excess emissions relatively scattered throughout the region, removed from the urban cores, and of a lesser magnitude than in the first map (Figure H-5).

From a planning viewpoint we would intuitively predict that emissions would be lessened in the planned situation, but the computer mapping presentation provides a clear and pointed visual clarification of this intuitive impression and herein lies its "graphic" merit.

Three pollutants were mapped for the Kansas City Region Study: sulfur oxides, suspended particulates, and carbon monoxides (see Figures D-19, 20, 21). These were differentiated by maximum, average, and minimum space heating days. The influence of space heating was calculated as a proportion of the total variable emissions.

3.4. MODELED AIR QUALITY

Modeled air quality was mapped for the Connecticut Study (Report F). In addition diffusion modeling of power plant emissions under different load conditions was carried out for the St. Louis Region Study (Report C) and the results mapped.

The diffusion model used by the Travelers Research Center for Connecticut was quite sophisticated in its use of a variable wind field. However, for stagnant conditions, even this model does not give results having a good correlation with air quality measured during the same period. Such a stagnant condition is shown for sulfur oxides in the first map of Figure F-4: a down valley (Connecticut River Valley) stable flow at noon time in October. It is evident from the symbolism used that the levels of air pollution are highest in the major urban areas of the state and spill out into Long Island Sound.

By contrast the second map in Figure F-4 shows the expected levels of sulfur oxides for a steady northwest wind at midnight in January. The predominant wind pattern shifts the highest levels of pollution from the urban core areas to downwind suburban and rural areas.

Comparison of these modeled air quality levels with actual measurements is essential to test the validity of the model calculations. Unfortunately, there are three sets of parameters which can affect the results:

(1) The emission inventory accuracy,

(2) the meteorological data and variable wind field used; this is particularly critical with stagnant conditions, and,

(3) the parameters in the model equations; for example the decay parameter influences how far downwind will the urban area pollution affect rural areas, as in the second map of Figure F-4.

Unfortunately, it is very difficult to design a verification program to isolate each of these three sets of parameters which may influence the modeling calculations. On October 15, 1968 from 2 to 4 p.m. a 46 station statewide monitoring network for sulfur oxides was activated as part of the verification. A surface of air quality was mapped from these 2-hour readings and is shown on the right in Figure F-5.

For the same time period, estimated emission inventory, and recorded meteorology, the TRC model was run to calculate sulfur oxides; calculations for the same 46 points (plus 7 additional receptor points) were mapped as shown on the left in Figure F-5. The two surfaces were then compared at the 46 measurement locations and the absolute differences between the observed and calculated values mapped. as shown in Figure F-6. The surfaces were not compared directly; only values at the data point locations were compared.

In the map on the left in Figure F-6 three categories of symbolism were used to show the differences between observed and calculated values;

(1) white areas; this shows the portion of the study area where the model is in close agreement with the observed values,

(2) dark areas (the 5 highest levels); this shows the portion of the study area where the model overcalculates the level of air quality. This includes most of the major urban areas, and

(3) light areas (the lowest level--dots); this shows the portion of the study area where the model undercalculates the air quality.

The degree of undercalculation is shown in the map on the right in Figure F-6. The white areas show the portion of the study area where the model overcalculates; the darker the symbolism the greater is the undercalculation in absolute terms.

Figure C-5 shows the concentrations for the St. Louis Region for the lowest combined cost dispatching from the various power plants. Most of St. Louis City and all of East St. Louis fall below a threshold level, whereas the southern part of St. Louis County, Granite City, and Alton all have high concentrations. Some caution should be exercised in interpreting variations on a scale much smaller than 20,000 feet (10,000 feet in the cities of St. Louis and Alton), for these distances are the grid sizes.

Figure C-4 shows the expected concentrations under the conventional lowest fuel costs for the same meteorlogical case and the same net demand as in Figure C-5. Values in Figure C-4 are roughly one level above the corresponding values in Figure C-5, indicating that concentrations must be generally twice as high.

Figure C-6 shows the SO_2 concentrations under dispatching without regard to "social cost", minus the concentration obtained under load shifting, or the improvement from the load-shifting model. It is evident from the map that Granite City benefits most from load-shifting, and that Alton and southern St. Louis County benefit to a lesser extent. The data value extremes printed below the map show that the improvement in concentrations rose to as high as 4.24 pphm, and extended in a wide band northward from the center of the core to the edge of the study area. The range of data on this "improvement" map does include negative values.

It should be noted that it was not really ground-level SO_2 concentrations, but rather population exposure to SO_2, that was to be reduced by the load-shifting model. To that end, two maps of the density of exposure to SO_2 (population density in persons/square mile times SO_2 concentration in ppm) were prepared: Figure C-7 shows dispatching based on fuel costs alone, and Figure C-8, dispatching to minimize total "combined costs". Figure C-7 indicates the region in which electric power generation helps cause an air pollution "problem", a high density of exposure to pollution.

The entire metropolitan core, including Alton and Granite City, is severely affected. Although the highest concentrations occur about 20 miles south of St. Louis, the whole city experiences a high density of exposure; in fact, the peak exposure density occurs about one mile north of downtown St. Louis, where the population density is greatest.

Juxtaposition of Figure C-5 (concentrations) and Figure C-7 (exposures) indicates that since East St. Louis, Illinois has only moderate levels of air pollution concentration, the high levels of exposure must be due to very high population density.

Figure C-9, better than any other single map, summarizes the results of the load-shifting model. The comparison of Figure C-9 with C-7 reveals that all the areas seen earlier to experience heavy exposure under fuel cost dispatching--Alton, St. Louis, East St. Louis--now enjoy substantial improvements. Overall, the patterns of the two maps are similar; the improvement map is about one level lower--indicating the 50% reduction in exposure which necessarily accompanies the corresponding reduction in concentrations.

3.5. BIOLOGICAL INDICATORS

In the Montreal Region Study, the study area was divided into two parts--the "rural" part and the "urban" part--by a boundary line approximately 10 miles from the city center. One of the objectives of the mapping was to focus on the biological data for the urbanized part of the Montreal area so that comparisons could be made with the conventional data.

Figure E-5 shows the Index of Atmospheric Purity (I.A.P.) over the urbanized area of Montreal for an equal value range distribution. The most polluted of the five categories contained more than one-third of the total number of data point values, and over six-sevenths of the urban values. Broadly speaking, the urban area corresponds to the limit of the area of "maximum" air pollution concentration, according to epiphyte sensitivity. If the simple number of epiphytes had been used as a proxy variable for the I.A.P., the distribution would have been reasonably close to the one for an equal value range.

The conventional data provided by the City of Montreal Department of Health dealt with three kinds of measurements: coefficient of haze (COH), sulfur dioxide (SO_2), and insoluble particulates (RES). The intended comparison (visual as well as statistical) between the biological and conventional data was hindered due to the very limited area covered by the three series of data. They dealt only with the central core of the urban area.

Figure E-7 shows the concentration of COH for the city of Montreal for 12 sampling stations.

In comparing the COH values with the I. A. P. values, only 9 data points were found to have sufficient spatial fit to be considered. The data series was much too small to offer meaningful statistical testing. The lack of relationship is not surprising in view of the fact that the I. A. P. is a long-term variable, while COH is not. Lichens and mosses need time (at least 3 to 4 months) to reflect increases in the level of air pollution and years to recover. Thus, their state at any time may reflect a previous air pollution incident, or, alternatively, may not yet have "caught up" with the present state of air pollution. Although expected for statistical reasons, the correlation coefficient found was deceptively low.

Figure E-8 shows the concentration of SO_2 for the city of Montreal. The 12 stations measuring SO_2 were generally located differently from those measuring COH. Figure E-9 shows the concentration of RES for the city of Montreal, measured at 15 sites. The statistical correlation of these pollutants with the I. A. P. was also meaningless; the air pollution data was extremely limited.

Because of limitations in the air monitoring network, there is not much local variation in the pollution surfaces as shown on the maps. For example when we compare Figure E-6 to the air pollution maps (Figures E-7 thru E-9), we see that the biological indicators show a more complicated pattern of pollution than the air monitoring system does.